National Park Service
U.S. Department of the Interior

Geologic Resources Division
Denver, Colorado

Canyonlands National Park

Geologic Resource Evaluation Report

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Executive Summary

This report has been developed to accompany the digital geologic map of Canyonlands National Park produced by Geologic Resource Evaluation staff. It contains information relevant to resource management and scientific research.

Each year the geologic resources of Canyonlands National Park draw thousands of visitors to the Moab area. The magnificent scenery, character, and beauty of Canyonlands National Park are the result of geologic processes, including erosion and mass wasting. In addition, structural features, seen at the surface today, are a consequence of Laramide and younger rejuvenation of preexisting fracture patterns of Precambrian age. The presence of salt at shallow depths—from the Middle Pennsylvanian Paradox Formation, the oldest rocks in the park—adds complexity to these landforms.

The primary audience for this report is resource managers. This report was compiled with the objective to present a description of geologic resources in the park in such a way as to provide information for making management decisions. The geologic setting and history are summarized in the introduction and geologic history sections. Map unit properties are organized into a table to facilitate access to the information and provide a link to the park's geologic map. Significant and interesting geologic features and processes are highlighted, which may be of use not only to resource managers but also interpretation and resource- protection staffs. Lastly, geologic resources that may warrant the attention of resource managers are a primary focus.

The following issues have been identified as having the most geological importance and the highest level of management significance:

- Abandoned Mine Lands (AML) Sites—Closures of AML sites in the park have been performed on a priority basis, with funding being the primary constraint. Eight mines (10 openings) were closed in Lathrop Canyon in February 1990. Since that time, park managers have closed six openings around Airport Tower and Upper Lathrop Canyon (November 1996), and in April 1998, seven openings were closed with bat gates: Upper Lathrop #9 and #12, Airport Tower #1 and #2, Musselman adit, and Shafer #1 and #2. District rangers have completed initial inventories for other remote sites. These inventories indicate that several other sites merit closure.

- Biological and Physical Soil Crusts—Biological soil crusts—composed primarily of cyanobacteria, lichens, and mosses—are important and widespread components of ecosystems in the park, namely in greatly benefiting soil quality. In some areas of the park, continued off- trail use by visitors and past trampling by cattle have significantly damaged soil crusts. Soil nutrient cycles, as well as most other benefits of biological soil crusts, have been compromised in these areas.

- Earthquake Potential—The Paradox basin contains complex structures and a number of faults known or suspected to have had Quaternary movement. Major Quaternary (?) faults that appear to extend below the evaporite sequence or that intersect the trend of the salt- anticline belt along preexisting structures can be regarded as potentially active faults that may experience significant tectonic displacements. Microseismic activity is not felt and has little potential for causing damage. During 1989, 421 events occurred within 2.5 miles (4 km) of the original underground potash mine workings. Some of these seismic events were human caused during mine dewatering. However, slightly stronger events have been recorded along the Colorado River to the south.

- Flooding—Flooding, erosion, and deposition by running water are the most active and potentially damaging hazards in the Canyonlands area. Torrential summer rains occasionally fill washes with runoff. Rock and earth debris that has collected in the washes for many seasons is then transported toward the Colorado River. Floodwaters in washes have been observed to move boulders larger than automobiles. Where floods cross roads and trails, damage occurs to infrastructure.

- Debris Flows—Investigators have linked debris flows in drainage basins to the presence and topographic position of shales within the watersheds in Canyonlands National Park. The presence of terrestrial shales, such as the Halgaito Shale, greatly increases the frequency of debris flows. The presence of shales in steep terrain is also critical.

- Landslides—Landslide deposits in Canyonlands National Park are associated with the Triassic- age Chinle Formation. However, landsliding is not considered a serious hazard unless a long series of wet years occurs.

- Rockfalls—Rockfalls occur sporadically along cliff walls as a natural process of erosional cliff retreat. Rock fragments from the Honaker Trail, Cutler, Moenkopi, Chinle, and Glen Canyon Group produce rockfall debris. In most cases, blocks of sandstone fall from the canyon rims and break up harmlessly on the slope below, but damage to highways and railroad tracks has occurred. Therefore, danger is possible in transportation corridors and to those using the area for recreational purposes.

- Decorative Stone—Rocks found in the vicinity of Canyonlands National Park have been used in the region as decorative stone for building facing, pavements, and gardens. Ripple- marked sandstone from the Moenkopi Formation; rounded metamorphic and igneous cobbles from Quaternary- age, higher- level terraces; and flat slabs of fossiliferous limestone from the Honaker Trail Formation have been collected for such purposes.

- Gold—Gravels of the Colorado River and terrace alluvium contain "flour" gold and rare flakes and small nuggets. Some of the gravels disturbed in the process of gold extraction have subsequently been exploited for sand and gravel.

- Sand and Gravel—Colorado River alluvium and terrace alluvium contain sand and gravel suitable for construction of highways. As of 1994, no attempt had been made to calculate the reserves, but they are expected to be large.

- Oil and Gas—The area surrounding Canyonlands National Park has been the site of widespread oil and gas exploration. Production in these fields has been from the Cane Creek zone of the Paradox Formation and from the Mississippian Leadville Formation. Oil shows also have been encountered in other layers of dolomite, shale, and anhydrite within the Paradox Formation.

- Salts—The most common salt minerals in the Paradox Formation are halite, carnallite, and sylvite. Because of its low potash content, carnallite is not considered commercial at present, but it remains a potentially valuable source of magnesium. Sylvite is the commercial potash mineral, which is used internationally as fertilizer. Carbonate, anhydrite, and black shale are potentially commercial brines. The Moab Salt Company currently operates the Cane Creek mine near the park, which produces potash and rock salt using solution mining and evaporation ponds.

- Uranium—The Chinle Formation in the Canyonlands area contains major deposits of uranium. Significant deposits also occur in the Morrison and Cutler Formations.

- Problem Soils—Building houses or constructing roadways over clay- bearing units of the Chinle Formation should be avoided on account of the presence of expanding and shrinking clay. Bentonite also makes dirt roads dangerous (slippery and unstable) when wet. In addition, piping is common in arid and semi- arid climates where fine- grained, non- cemented, Holocene- age alluvium is incised by ephemeral stream channels. Piping involves the removal of fine particles increasing void space and thereby producing a "pipe" and promoting enhanced erosion.

- Wetlands—Wetlands are important ecosystems because they stabilize stream banks, act as filters to improve water quality, attenuate flood waters, and enhance biodiversity (i.e., provide habitat for amphibians, reptiles, birds, including threatened and endangered species). They also are highly productive in terms of biomass and nutrient productivity, and are valuable water sources for wildlife and recreationists. Human impacts to wetlands include building parking lots and structures in or near stream channels, building structures in floodplains (e.g., culverts and bridges), grazing in uplands and stream channels, roads and trails in streambeds, introduction of exotic species, and impacts from flow regulation and diversion. In addition, agricultural activities and past extirpation of beaver have affected wetlands.

- Wind Erosion—Eolian dust (windblown silt and clay) is important in desert ecosystems as a source of nutrients and as a substrate for biological soil crusts, which stabilize arid surfaces and cycle nitrogen. On the other hand, the presence of eolian dust in arid- land surficial deposits and soils renders these deposits vulnerable to wind erosion. Sand blowing across and accumulating on roads occasionally causes problems. More commonly, motorists using back roads should be cautious when proceeding into areas of sheet or dune sands. Loss of traction in sandy areas becomes more pronounced during the hot summer months when even gentle slopes of sand cannot be traversed in a motor vehicle. Trampling and vegetation alteration by prior livestock grazing within the park, and human recreational activities (e.g., hiking, biking, and driving, especially off established trails and roads) can destabilize soils and increase soil susceptibility to wind erosion.

Introduction

The following section briefly describes the regional geologic setting and the National Park Service Geologic Resource Evaluation Program.

Purpose of the Geologic Resource Evaluation Program

Geologic resources serve as the foundation of park ecosystems and yield important information needed for park decision making. The National Park Service Natural Resource Challenge, an action plan to advance the management and protection of park resources, has focused efforts to inventory the natural resources of parks. The Geologic Resource Evaluation (GRE) Program, administered by the NPS Geologic Resources Division, carries out the geologic component of the inventory. The goal of the GRE Program is to provide each of the identified 274 "natural area" parks with a digital geologic map, a geologic resource evaluation report, and a geologic bibliography. Each product is a tool to support the stewardship of park resources and each is designed to be user friendly to non- geoscientists. In preparing products the GRE team works closely with park staff and partners (e.g., USGS, state geologic surveys, and academics).

The GRE teams hold scoping meetings at parks to review available data on the geology of a particular park and to discuss the geologic issues in the park. Park staff is afforded the opportunity to meet with the experts on the geology of its park. Scoping meetings are usually held in each park individually to expedite the process although some scoping meetings are multi- park meetings for an entire Vital Signs Monitoring Network.

Geologic Setting

Sparsely vegetated plateaus, mesas, deep canyons, and barren badlands characterize the scenic beauty of the Colorado Plateau, which encompasses an area of approximately 140,000 square miles (36,260 km^2) in the Four Corners region of Utah, Colorado, Arizona, and New Mexico. The Colorado Plateau includes the area drained by the Colorado River and its tributaries: Green, San Juan, and Little Colorado Rivers.

The combination of high relief and an arid climate over most of the plateau has resulted in limited plant cover. The products of weathering are easily eroded by fast moving streams leaving behind bare rocks that produce the dramatic scenery and excellent rock exposures of the area.

Elevations on the plateau range from 3,000 to 14,000 feet (914 to 4,267 m) with an average of 5,200 feet (1,585 m). The range of elevation causes climate extremes—Sonoran desert to alpine; however, semiarid conditions prevail. The high Sierra Nevada to the west prevents Pacific moisture- laden air from reaching the southwestern states. As a result of this rain shadow effect, annual precipitation on the Colorado Plateau is low, averaging about 10 inches (25.4 cm) per year.

General Physiography

The Colorado Plateau is a high- standing crustal block of relatively undeformed rocks surrounded by the highly deformed Rocky Mountains and Basin and Range. The Uinta Mountains of Utah and the Rocky Mountains of Colorado define the northern and northeastern boundaries of the plateau. The Rio Grande Rift Valley in New Mexico defines the eastern boundary. The southern boundary is marked by the Mogollon Rim, an erosional cuesta that separates the Colorado Plateau from the extensively faulted Basin and Range Province. A broad transition zone, where geologic features range between those typical of Colorado Plateau and Basin and Range, lies to the west. The margins of the Colorado Plateau are marked by major volcanic accumulations.

Geophysical studies indicate Earth's crust is relatively thick below the province and heat flow (geothermal gradient) is relatively low. The plateau also has distinct gravity and magnetic signatures.

Rigby (1977) divided the Colorado Plateau into six sections: (1) Grand Canyon section—structurally the highest part of the Colorado Plateau province; (2) High Plateaus section—characterized by high, north- trending plateaus, separated from each other by faults; (3) Uinta Basin—structurally the lowest part of the Colorado Plateau; (4) Canyonlands section—deeply incised canyons, large monoclines, and laccolithic mountains; (5) Navajo section—scarped plateaus, less dissected than in the Canyonlands section; and 6) Datil section—largely volcanic in origin (fig. 1).

Geologic Structures

The major structures of the plateau include broad flexures, monoclines, vertical faults, and salt tectonic features, as well as igneous laccoliths and volcanics. Moreover, rather than the tight folds characteristic of orogenic belts, folds of the Colorado Plateau are broad open folds or flexures. As an example, the Kaibab Uplift forms a great arch 100 miles (160 km) long and 25 miles (40 km) wide.

Wide areas of nearly flat- lying sedimentary rocks are separated by abrupt bends of strata along monoclinal (one- sided) folds. Monoclines form where sedimentary rocks are draped over deep- seated basement faults. Classic examples of monoclines on the Colorado Plateau include the north- south trending Comb Ridge monocline on the east flank of the Monument uplift, the San Rafael Reef, and the Waterpocket Fold at Capitol Reef National Park.

A number of long north- south trending normal faults dissect the plateau. A normal fault forms by tensional forces and is defined as a fault where the foot wall has moved up relative to the hanging wall. The Hurricane Cliffs west of Zion National Park are an impressive west-facing scarp that is the surface expression of one of these faults. In Grand Canyon, the Bright Angel fault defines the orientation of Bright Angel Canyon.

The Colorado Plateau is actually a series of plateaus separated by north- south trending faults or monoclines. The faults are more prevalent to the west and monoclines tend to occur to the east. Formation of faults and monoclines is due to movement of crustal blocks in the Precambrian basement rocks. Differential movement of these blocks is responsible for the differences in elevation across the plateau.

Two types of igneous features occur on the plateau: intrusive laccoliths and extrusive volcanics. Laccoliths are concordant igneous bodies, which form when magma is injected at shallow depths along the bedding planes of sedimentary rocks that results in doming of overlying strata. Examples of laccoliths include the Henry, La Sal, Abajo, Ute, La Plata, and Carrizo Ranges. The Henry Mountains, where G. K. Gilbert first described laccoliths and proposed their name, can be viewed at Capitol Reef National Park, and the La Sal Mountains at Arches National Park. The laccoliths are Oligocene to Miocene in age and have an intermediate composition. The volcanics on the plateau were deposited less than 6 million years ago and are as young as 1,200 years old. The older volcanics are andesitic, whereas the younger volcanics are dominantly basaltic in composition and occur as lava flows and cinder cones. In some areas, lava flowed down preexisting valleys; the softer sedimentary rocks that once formed the sides of the valley have been eroded away leaving the lava flows exposed as a ridge or inverted topography.

Thick accumulations of salt deposits occur in the subsurface of the Paradox basin of the eastern Colorado Plateau. Because salt has a low density and is very ductile, it flows under pressure and rises toward the surface, deforming overlying strata as it moves. Excellent examples of salt anticlines and salt domes can be observed at Canyonlands National Park.

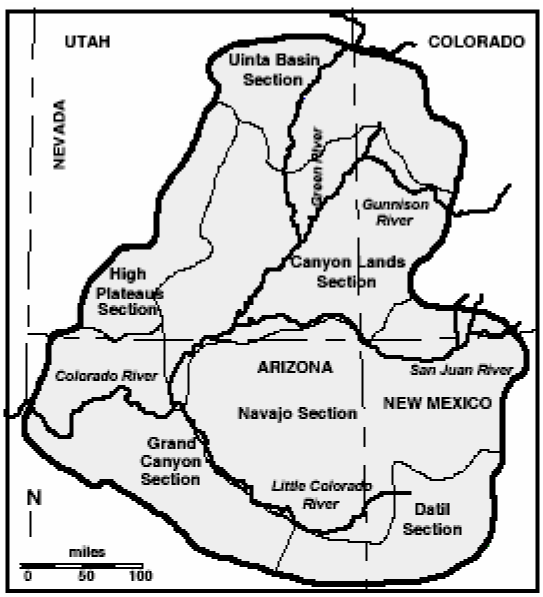

Figure 1. Map of the Colorado Plateau Province. The Colorado Plateau, of which Canyonlands National Park is a part, can be divided into six sections. This map shows the major drainage and section boundaries. ***Source*****: Hunt (1956).**

Geologic Issues

Scoping sessions were held for Canyonlands National Park on May 24–27, 1999, and June 3–6, 2002, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs (see appendices). The following section synthesizes the scoping results, in particular, those issues that may require attention from resource managers.

Included in this section are recommendations for potential research, inventory, and monitoring projects, which participants discussed at the geoindicators scoping meeting in June 2002. The scoping summary for the Southeast Utah Group geologic resources inventory workshop is included as Appendix B. The scoping summary for the geoindicators meeting is included as Appendix C; the complete report and meeting notes can be found on the included CD (Attachment 1).

Readers are referred to figure 2 (at the end of this section) for an index map that shows localities discussed in this report and figure 3 (at the end of this section) for a generalized stratigraphic column for rock units discussed in this report.

Abandoned Mine Land Sites

Thirty- one abandoned mine land (AML) openings at 10 sites exist within the boundaries of Canyonlands National Park (table 1). Investigators identified the openings located in Lathrop Canyon, in the northeastern section of Island in the Sky, as highest priority for mitigation because of easy access and the presence of hazards to park visitors. The mines were connected by a service road and cattle trail, which today, though washed out and overgrown in places, serves as a popular hiking trail. The mines were not extensively developed (maximum depth of 280 feet [85 m]), attesting to the low grade of uranium ore at this location. All workings are essentially horizontal because they are developed on outcrops of the flat- lying Shinarump Member of the Chinle Formation, which is typically no more than 10 feet (3 m) thick. Average mine drift dimensions are 6 feet (1.8 m) wide by 7 feet (2.1 m) high, while some chambers open to a maximum of 25 feet (7.6 m) wide by 11 feet (3.4 m) high.

Old campfire rings and footprints indicate that visitors have been accessing the mines despite general warning signs posted by park managers. Alpha radiation levels inside the deeper mines approaches and exceeds occupational limits for entry in the mine without breathing protection. Radiation in the mines precludes camping, which may have been more tempting inside the mines because they provide cool retreat from the hot desert sun and serve as a refuge from the torrential rains which occasionally drench the area. Additional hazards include explosives that have been found in the area, and clayey areas of the mines that become very slick when wet, adding to the potential for serious injury from rusty scrap steel and nails. Although rock in the area is generally stable, some loose slabs were found and rockfalls could occur.

Table 1. AML sites in Canyonlands National Park

Name	Location	Adits	Shafts	Total
Lathrop Canyon	T27S, R19E, s34,35	12	0	12
Airport Tower	T28S, R19E, s2,3	6	0	6
Musselman	T24S, R21E, s3	1	0	1
Shafer	UTM, 603000E, 4255000N	2	0	2
Buck Canyon	T28S, R19E, s29,29	3	1	4
Taylor Canyon Campground	UTM 593000E, 4258000N	2	0	2
Woodruf Bottom	UTM 585000E, 4263000N	1	0	1
Saddle Horse Bottom	UTM 578000E, 4261000N	1	0	1
Salt Creek (Needles)	T31S, R20E, s7	1	0	1
Cathedral Point Mesa (Needles)	T32S, R20E, s28	1	0	1
Total				31

***Source*: John Burghardt, NPS Geologic Resources Division, unpublished data, April 21, 1998.**

In the early years of the park, the Lathrop Canyon mining area did not attract many visitors. However, visitation to the area eventually began to increase, and in 1988, at the request of park managers and the NPS Rocky Mountain regional director, staff from the Geologic Resources Division (formerly known as the NPS Mining and Minerals Branch) inventoried the mines. They determined that the potential for rockfall from the mine roofs in eight of the mines posed a safety hazard that required physical closure. Several of the deeper adits had significantly elevated alpha radiation readings (from radon gas and its progeny), although radiation at mine portals was within acceptable levels due to dilution with uncontaminated outside air. These eight mines (10 openings) were closed with cable nets in February 1990

(Craig Hauke, Southeast Utah Group, unpublished environmental assessment, August 1996). In addition, a French drain system was installed at mine #7, an opening with water drainage.

Special signs warning of elevated radiation levels, contaminated water, and camping prohibitions were developed for this project, and installed just inside the cable net closures. These signs have been very effective at deterring vandalism of the closures and keeping visitors from remaining in the area long enough to receive a significant dose of radiation. Furthermore, other National Park System units and agencies have since used the sign design at their uranium AML sites.

Since 1990, park managers have closed six openings around Airport Tower and Upper Lathrop Canyon using earthen hand- backfills. In April 1998, seven openings were closed with bat gates, which allow bat but not human entry: Upper Lathrop #9 and #12, Airport Tower #1 and #2, Musselman adit, and Shafer #1 and #2.

The NPS Geologic Resources Division arranged all the work to close the abandoned mines through the engineering, contracting, and project management assistance of the Utah Department of Natural Resources, Division of Oil, Gas and Mining's Abandoned Mine Land Reclamation Program. This partnership between the National Park Service and the Utah Department of Natural Resources has proven to be very successful for addressing AML sites in all of the National Park System units in Utah (John Burghardt, NPS Geologic Resources Division, written communication, January 2004).

Mine closures in the park have been performed on a priority basis, with funding being the primary constraint. District rangers have completed initial inventories for remote sites. From these inventories it appears that several other sites merit closure (John Burghardt, NPS Geologic Resources Division, written communication, January 2004).

Biological and Physical Soil Crusts

Biological soil crusts—composed primarily of cyanobacteria, lichens, and mosses—are important and widespread components of the ecosystems in the park, namely in benefiting soil quality. Soil crusts increase water infiltration in some soil types, stabilize the soils, fix atmospheric nitrogen for vascular plants, provide carbon to the interspaces between vegetation, secrete metals that stimulate plant growth, capture nutrient- carrying dust, and increase soil temperatures by decreasing surface albedo. They affect vegetation structure directly due to effects on soil stability, seedbed characteristics, and safe-site availability, and indirectly through effects on soil temperature and on water and nutrient availability. Decreases in the abundance of biological soil crusts relative to physicochemical crusts—which can protect soils from wind erosion but not water erosion, and do not perform other ecological functions of biological crusts—can indicate increased susceptibility of soils to erosion and decreased function of other ecosystem processes associated with biological crusts.

Continued off- trail use by visitors and past trampling by cattle have significantly damaged soil crusts in some areas of the park. Soil nutrient cycles, as well as most other benefits of biological soil crusts, have been compromised in these areas.

Recommendations
1. Map biological soil crust communities and inventory condition and distribution of biological soil crusts.
2. Investigate connection between ecosystem function and biological crusts.
3. Study crust recovery rates and susceptibility to change.
4. Study crust population dynamics and conditions.

Problem Soils

Swelling Clays

Because of potential for expanding and shrinking, building houses or constructing roadways over clay-bearing units of the Chinle Formation should be avoided (Doelling and others, 1994). The Petrified Forest Member of the Chinle Formation contains bentonite, which makes dirt roads dangerous when wet (Baars, 2000).

Piping

Piping is subsurface erosion by groundwater that flows into permeable, non- cohesive layers in unconsolidated sediments. During piping, water removes fine sediments and exits at a spot where the layer intersects the surface. The removal of fine particles increases void space thereby producing a "pipe" and enhancing erosion. Fine- grained soils and surficial deposits are prone to piping and gullying. Piping is common in arid and semiarid climates where fine- grained, non- cemented, Holocene- age alluvium is incised by ephemeral stream channels (Doelling and Morgan, 2000). Floods caused by cloudburst storms can quickly remove large volumes of material.

Earthquake Potential

In a broad sense, the interior of the Colorado Plateau is tectonically stable and has simple crustal structure. Much of the region shows little or no evidence of tectonism during the Quaternary. However, the 1988 M_L 5.3 San Rafael Swell earthquake, which occurred on a buried fault, demonstrates a potential for moderate- size earthquakes in the Colorado Plateau (Nava and others, 1988).

Unlike the regional picture, the Paradox basin contains complex structural relations and a number of faults known or suspected to have had Quaternary movement. A conspicuous group of high- angle, northwest-trending, valley- bounding faults is associated with dissolutional collapse along the crests of large salt anticlines, cored by evaporite- rich strata of the Pennsylvanian Paradox Formation. These normal faults may be favorably oriented with respect to the regional stress field, which on the basis of low- level seismicity appears to be characterized by northeast- oriented extension (Wong and Humphrey, 1989; Zoback and Zoback, 1989). From a study of relative fluvial- incision rates during the late Cenozoic, Ely (1988) recognized a regional northwest- trending downward axis between Castle- Sinbad- Paradox Valleys and the Uncompahgre uplift, which he attributed to extensional reactivation of deep- seated faults beneath the Paradox basin. Major Quaternary (?) faults that appear to extend below the evaporite sequence (for example, the Moab fault and possibly the Lisbon Valley fault zone) or that intersect the trend of the salt- anticline belt along preexisting structures (for example, the Shay graben) can be regarded as potentially active faults that may experience significant tectonic displacements (Woodward- Clyde Consultants, 1982).

Surface faulting related strictly to salt dissolution and collapse represents an unknown (probably low) seismic hazard. Youthful salt- related deformation along the Colorado River (in particular, the Needles graben and Meander anticline) is a local, shallow- seated response to canyon cutting and associated topographic relief and thus probably does not occur seismically. Much of the most recent deformation in the Paradox basin is due to continued collapse of salt- cored valleys and is expressed as tilted and warped surficial deposits, rather than as discrete surface fault ruptures. This type of deformation may occur gradually and not as a succession of instantaneous events (Hecker, 1993).

Wong (1984) and Wong and Humphrey (1989) studied seismicity in the Paradox basin from 1979 to 1987 in connection with nuclear waste- disposal investigations. Very low- level earthquake activity was noted along the Colorado River from its confluence with the Green River northward to Amasa Back. The strongest recorded event (Richter magnitude 3.8) occurred February 1, 1967, with its epicenter near Upheaval Dome (Woodward- Clyde Consultants, 1980). Most of the events occurring in the region are microearthquakes having Richter magnitudes of less than 1.0.

During 1989, 421 seismic events occurred within 2.5 miles (4 km) of underground potash mine workings outside the park(Wong and Humphrey, 1989). The old workings are generally flooded with water, which hydrostatically supports the roof. The mine is periodically dewatered (about once a year) for brine extraction, during which time earthquake events increase. However, slightly stronger events have been recorded along the river to the south. Microseismic activity is not felt and has little potential for causing damage (Doelling and others, 1994).

Flooding

According to Doelling and Morgan (2000), flooding, erosion, and deposition by running water are the most active and potentially damaging hazards in the Merrimac Butte quadrangle (northeast of the park). Sparsely vegetated, steep fan slopes and deep, narrow washes are subject to flooding and to rapid erosion from waters generated by cloudbursts. Debris flows and floods generally remain confined to stream channels in high- relief areas, but may exit channels and deposit debris where slope gradients decrease or channels are shallow along their travel paths. Easily erodible bedrock and abundant unstable slope debris provide ample material for debris flows. Debris flows and stream floods have damaged roads in the Merrimac Butte quadrangle (Doelling and Morgan, 2000).

Torrential summer rains occasionally fill washes with runoff. Rock and earth debris that has collected in the washes for many seasons is then transported toward the Colorado River. Floodwaters in washes have been observed to move boulders larger than automobiles. Damage occurs where floods cross roads and trails. Motorists should not attempt to cross washes in flood stages, and hikers should stay out of narrow canyons when thunderstorms are imminent (Doelling and others, 1994).

Three geohydrologic processes are related to flooding: (1) stream channel morphology, (2) streamflow, and (3) stream sediment storage and load. Participants at the geoindicators scoping meeting in June 2002 identified these three processes as highly important to the park's ecosystem and highly significant for natural resources managers. They also were interpreted as being significantly impacted by (or having high potential for) impacts by human activities, including parking lots and structures in or near channels, structures in floodplains (e.g., culverts and bridges), livestock grazing in uplands and stream channels, roads and trails in streambeds, introduction of exotic species, and impacts from flow regulation and diversion (Geoindicator scoping meeting, unpublished report, June 2002).

Stream Channel Morphology

Stream channels are vital components of aquatic and riparian ecosystems in arid- land parks. The morphology of stream channels impacts the vegetative structure of riparian corridors, affects the height of the water table, and affects the energy of water flow downstream (which affects erosion rates and water quality).

Recommendation

1. Conduct hydrologic condition assessment to identify actual and potential "problem reaches" of streams and prioritize for monitoring, including repeat aerial photographs and cross sections. Some data are available for the park (e.g., cross sections for Salt Creek in the Needles district) (Geoindicators scoping meeting, unpublished report, June 2002).

Streamflow

Streamflow is critical to the maintenance of aquatic and riparian ecosystems. Streamflow impacts the structure of the riparian corridor and affects the height of the water table, water quality, and erosion rates.

Existing gauging stations are located on the Green River (Green River, Utah), San Rafael River (near Green River, Utah.), Fremont River (at Cainville, Utah, and above Park at Pine Creek), and on the Muddy River. Many other gauging stations exist (see http://water.usgs.gov/nasqan/progdocs/factsheets/clrdfact/clrdfact.html). Other relevant data may be obtained from local U.S. Geological Survey, Water Resources Division.

Recommendations
1. Identify important hydrologic systems that would benefit from knowledge of streamflow.
2. Research effects of land use and climatic variation on streamflow.
3. Investigate paleoflood hydrology.

Stream Sediment Storage and Load

Stream sediment storage and load is an important indicator of ecosystem health because sediment loads and distribution affect aquatic and riparian habitats, and because sediment loading can result in changes to channel morphology and frequency of overbank flooding.

Recommendations
1. Conduct research concerning ungauged stream sediment storage and load. No data are available except on the main stem of the Colorado River at Cisco, Utah, and the Green River at Green River, Utah.
2. Measure sediment load on streams of high- interest for comparative assessment. Data will provide information for making management decisions.

Groundwater Level

Groundwater is a limited resource, and the potential for depleting the resource is significant, although current human impacts have not been quantified. Outside the river corridors in Canyonlands National Park, groundwater supplies much of the water available for wildlife, and supplies 100% of the park's water supply for human use (Geoindicators scoping meeting, unpublished report, June 2002).

Recommendations
1. Inventory and research groundwater quality, level, and discharge.
2. Install transducers and data- loggers in wells.
3. Develop methods for measuring water discharge from seeps and hanging gardens.
4. Investigate additional methods to characterize groundwater recharge areas and flow directions.

Groundwater Quality

The quality of the groundwater at Canyonlands National Park impacts hanging gardens—features that contain rare and unique plant species—and provide important wildlife habitat. The quality of groundwater is also a safety and health issue with respect to human use (Geoindicators scoping meeting, unpublished report, June 2002).

The potential for negative effects on groundwater by human activity is significant. For example, in Canyonlands National Park an old landfill in the Needles district (about 1 mile [1.6 km] from the visitor center and 3,000 feet [914 m] from a domestic well) had unregulated dumping from 1966 to 1987, and oil- well sites had on site disposal of drilling waste. The effects of mining and oil and gas drilling are unknown. However, inadequately abandoned oil and gas wells within and close to the park's boundaries may result in saline waters infiltrating into groundwater supplies. Other potential impacts include: (1) herbicide use to decrease tamarisk populations, (2) trespass cattle at springs, (3) impacts from recreational uses (these have not been quantified), and (4) the Moab Salt Company potash mine located on the Colorado River at Potash, Utah.

Recommendations
1. Locate and inventory all seeps, springs, and hanging gardens.
2. Prioritize seeps, springs, and hanging gardens for assessment of water quality.
3. Acquire oil and gas well records potentially connected to the park's groundwater systems. Assess quality of groundwater isolation.
4. Use geochemical indicators to investigate groundwater flow areas, flow directions and recharge area, and groundwater age.
5. Identify and study potential sources for groundwater quality impacts.

Mass Wasting

Debris Flows

Investigators have linked debris flows in drainage basins less than 347 square miles (900 km^2) to the presence and topographic position of shales within the watersheds in Grand Canyon and Canyonlands National Parks. The presence of terrestrial shales, such as the Hermit Shale in Grand Canyon and Halgaito Shale in Canyonlands, greatly increases the frequency of debris flows. The presence of shales in steep terrain is also critical. Previous research in these parks indicates that kaolinite and illite are the dominant clay minerals in debris- flow producing shales, whereas smectites and sodium cations are high in shales that do not produce significant debris flows (Griffiths and others, 1997).

Investigators hypothesize that the frequency of debris flows from sedimentary terrane on the Colorado Plateau is related to the mineralogy and cation chemistry of shales. Using 1:250,000 geology maps, they identified 33 geologic formations in this region that contain shale units. They sampled 26 of these formations (35 units), associated colluvial wedges (24 samples), and debris-flow deposits (16 samples) for clay mineralogy and major cations. In general, shales of terrestrial origin—either lacustrine or fluvial—produce debris flows, whereas marine shales rarely produce debris flows that travel significant distances beyond the initiation point. Debris-flow producing shales generally contain greater than 50% illite and kaolinite and less than 10% smectites and relatively high concentrations of exchangeable potassium (K) (2–15%) and magnesium (Mg) (5–20%) and less than 15% sodium (Na) (exceptions: Straight Cliffs Formation and one unit of the Chinle Formation). Shales that rarely produce debris flows contain less than 40% smectite, generally greater than 20% Na, and only small concentrations of K and Mg.

Factor analysis of the mineralogy and cation data clearly differentiates the two types of shales. Colluvial wedges have similar mineralogies to the parent shale units, except many contain significant amounts of smectites and Na, possibly owing to pedogenesis and eolian deposition. The mineralogy and cation chemistry of debris- flow hazards on the Colorado Plateau may be mostly explained by the location and topographic position of terrestrial shales (Griffiths and others, 1997).

Landslides

Landslide deposits in Canyonlands National Park are associated with the Triassic- age Chinle Formation (e.g., around Upheaval Dome and Grand View Point, and northeast of Red Sea Flat in the northeast corner of the park) (Huntoon and others, 1982). Landsliding is not considered a serious hazard on the nearby Gold Bar Canyon quadrangle and should not be unless a long series of wet years occurs (Doelling and others, 1994). The close proximity and similar terrain makes this information an acceptable analog for Canyonlands National Park.

Only two significant landslide deposits are present in the Gold Bar Canyon quadrangle: (1) on the northeast side of Moab Canyon and (2) in a tributary of Little Canyon. First, a block of the Salt Wash Member of the Morrison Formation, which is a rock unit not present in the park, detached along a clayey redbed and moved across the trace of the Moab fault and over the top of the Cutler Formation (present in the park). The landslide is considered inactive (Doelling and others, 1994). Second, a jumbled mass of ledgy sandstone and fine- grained clayey horizons from the Chinle Formation (present in the park) has oozed over the Moenkopi Formation (present in the park) like a viscous debris flow. This landslide is considered stable (Doelling and others, 1994).

Rockfalls

Rockfalls occur sporadically along cliff walls (generally Wingate Sandstone) as a natural process of erosional cliff retreat. Rock fragments from the Honaker Trail, Cutler, Moenkopi, Chinle, and Glen Canyon Group (including Wingate Sandstone) produce rockfall debris (Doelling and Morgan, 2000). In most cases, blocks of sandstone fall from the canyon rims and break up harmlessly on the slope below, but damage to highways and railroad tracks has occurred (Doelling and others, 1994). The most susceptible cliffs are those broken by fractures that run subparallel to cliff faces (Doelling and Morgan, 2000).

The high cliffs southwest of the Moab fault are active rockfall areas (Doelling and Morgan, 2000). Rockfall debris may travel great distances downslope during rockfall events. Because Canyonlands National Park is uninhabited, hazards to human life only occur in transportation corridors and to those using the area for recreational purposes.

Evidence for recent rockfall events includes the lack of desert varnish on cliff faces, where blocks have detached, and fresh rubble on the slopes below cliff faces. Rockfalls occur more regularly where joints parallel the cliff face. Generally, soft underlying units, which provide support for hard rocks of the cliffs, are eroded back under cliff faces by groundwater moving laterally to the cliff edges above less permeable slope formers. The undercutting removes support from beneath the massive sandstone cliffs and promotes rockfalls (Doelling and others, 1994).

Serving as an example for Canyonlands National Park, rockfalls near Dead Horse Point State Park in 1984 and in Castle Valley is 1985 were recorded by a 17- station microearthquake network that was monitoring the seismicity of the Canyonlands region. The two events were the largest rockfalls recorded in the eight years of network operation, although they were not triggered by earthquakes. Both rockfalls occurred in Wingate Sandstone above soft shale at its contact with the Chinle Formation and had volumes of approximately 240,113 cubic feet (6,800 m^3). The duration of the Dead Horse rockfall was approximately 64 seconds, equivalent to a Richter magnitude M_L 1.8. The duration of approximately 140 seconds of the Castle Valley rockfall suggests an equivalent M_L 2.8 (Wong, 1989).

Mineral Resources

The extraction of energy resources and the collection of mineral specimens within Canyonlands National Park is strictly prohibited.

Decorative Stone

Rocks found in the vicinity of Canyonlands National Park have been used in the region as decorative stone for building facing, pavements, and gardens. Ripple- marked sandstone from the Moenkopi Formation; rounded metamorphic and igneous cobbles from Quaternary- age, higher- level terraces; and flat slabs of fossiliferous limestone from the Honaker Trail Formation have been collected for such purposes (Doelling and others, 1994).

Gold

The gravels of the Colorado River and terrace alluvium contain “flour” gold and rare flakes and small nuggets. A small, but unknown quantity of gold was recovered in the Gold Bar Canyon quadrangle from past operations carried out adjacent to Gold Bar and Jackson Bottom. The gold occurs in black, magnetite- bearing, coarse sandy lenses in river gravels. The gold content is generally uniform vertically in the individual gravel bars. The upstream ends of bars and higher- level terraces may be slightly richer (Butler, 1920). Some of the gravels disturbed in the process of gold extraction have subsequently been exploited for sand and gravel (Doelling and others, 1994).

Oil and Gas

The area immediately surrounding Canyonlands National Park, in particular the Gold Bar Canyon quadrangle, has been the site of widespread exploration with production of oil and gas in the Long Canyon, Cane Creek, Big Flat, and Bartlett Flat fields. Production in these fields has been from the Cane Creek zone of the Paradox Formation and from the Mississippian Leadville Formation. Oil shows have also been encountered in other intervals of dolomite, shale, and anhydrite within the Paradox Formation (Doelling and others, 1994). In addition, oil and gas production occurs in the vicinity of the park from the Dakota, Morrison (Salt Wash Member), Entrada, and Wingate Formations.

As of December 1992, 948,000 barrels of oil had been produced from the Long Canyon field in the vicinity of Canyonlands National Park. No wells had been successfully completed in the Cane Creek field. The Big Flat and Bartlett Flat fields were abandoned in 1988 and 1965 respectively. However, the successful completion of the Kane Springs Federal 27- 1 well in the Bartlett Flat field, by Columbia Gas and Development Corporation in April 1991, renewed interest in oil and gas development in the area (Doelling and others, 1994).

Salts

The Paradox Formation, estimated at 3,300 to 7,000 feet (1,005 to 2, 134 m) thick, underlies Canyonlands National Park. The thicker sections may be due to complex flowage and folding of salt layers. In the deepest parts of the Paradox Formation, investigators have identified 29 cycles of halite (common salt) precipitation and associated clastic deposition (Hite, 1960). Seventeen of the 29 cycles contain potash salts, but only 10 are rich or thick enough to be potentially commercial (Gwynn, 1984). Thickness of individual cycles was controlled by the supply of water from the sea, evaporation rates, climatic changes, position in the basin, and tectonic activity. A cycle began with a rise in sea level and a freshening of water in the basin (Peterson and Hite, 1969). The depositional sequence commenced with the precipitation of anhydrite followed by dolomite and finally deposition of calcareous black shale. Thereafter, the gradual return to restricted conditions deposited anhydrite again with black shale and salt. The end of the cycle was marked by a disconformity produced at the beginning of the next cycle as the water again freshened. The 29 cycles, which are numbered in descending order, are rarely all present in one geographic area, and generally individual cycles are incomplete.

According to Baars (2000), thickness of the gross salt section varies from zero at the Four Corners area and mouth of Gypsum Canyon in Cataract Canyon to well over 4,000 feet (1,219 m) in the heart of the basin., Because salt had begun to flow into salt piercement anticlines along the large, rejuvenated basement fault blocks, resulting thicknesses vary widely, making estimates of the depositional thickness of salt that may have accumulated in the eastern, deepest part of the Paradox basin prior to Late Pennsylvanian time difficult.

The most common salt minerals in the Paradox Formation are halite, carnallite, and sylvite (Ritzma, 1969). Because of its low potash content, carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$) is presently not considered commercial, but it remains a potentially valuable source of magnesium. Sylvite (KCl) is the commercial potash mineral, which is used internationally as fertilizer. Carbonate, anhydrite, and black shale are commonly lumped together and identified as marker beds, which are potentially commercial brines. The unusually high quality of the formation could be due to secondary enrichment caused by local reconcentration of an earlier, more widespread lower- grade deposit prior to the deposition of the overlying marker bed (R.R. Norman, Buttes Gas and Oil Company, written communication, 1970).

Texas Gulf Sulphur, Inc. started development at the Cane Creek potash mine in 1963, including sinking shafts and constructing roads, railroads, and the beneficiation plant. On August 28, 1963, the company suffered a devastating methane gas explosion in the incline shaft—going from the bottom of the vertical shaft at 2,850 feet (869 m) to the ore deposit at about 4,000 feet (1,219 m). The contract miners—all from hard- rock mining and not familiar with methane, which is common in coal mining—ignored the methane- gas occurrences until too late and 18 contract miners were killed during the explosion (Phil Cloues, NPS Geologic Resources Division, written communication, January 2004).

The mine reopened with limited production in 1964. During the early to mid 1970s the whole mine was closed and converted to a solution mine with no underground mining. The now- Texas Gulf, Inc. (a name change occurred in the late 1970s) was then absorbed into Societe Nationale Elf Aquitaine, Inc., and Williams Acquisition Holding Company, Inc., which included the solution mine near Moab (about 25 miles [40 km] down the Colorado River but almost due west of Moab as the crow flies). In April 1996 Texas Gulf, Inc. sold the mine to Moab Salt, Inc., which is a subsidiary of Potash Corporation of Saskatchewan, the largest fertilizer company in the world. Potash Corporation of Saskatchewan sold the company in April 2001 to Intrepid Oil and Gas (Denver, Colorado). The Moab Salt Company, now a subsidiary of Intrepid Oil and Gas, currently operates the mine, which produces potash (KCl and K_2SO_4) and rock salt (NaCl) using solution mining and evaporation ponds along the Colorado River (Phil Cloues, NPS Geologic Resources Division, written communication, January 2004).

Sand and Gravel

Colorado River alluvium and terrace alluvium contain sand and gravel suitable for construction of highways. The Utah Department of Transportation conducted tests on the deposits in two localities: Gold Bar and Jackson Bottom, and found them suitable for use as roadbase and surfacing materials. The quality of the sand and gravel in the terraces and alluvium along the river is not expected to vary. No attempt was made to calculate the quantity of sand and gravel, but they are expected to be large. Such sand and gravel was put to use in the construction of Utah Highway 279 that connects Moab and Potash (Doelling and others, 1994).

Uranium

The Chinle Formation in the Canyonlands area contains major deposits of uranium. Significant deposits also occur in the Morrison and Cutler Formations. As of January 1, 1975, nearly 76.5 million pounds of uranium oxide (U_3O_8) had been produced from the area, representing 14% of the total U.S. production. Lisbon Valley, the most important uranium district in the Canyonlands area, has produced slightly more than 60 million pounds of U_3O_8 or 78% of the area's total (Chenoweth, 1975).

The abandoned Lathrop Canyon mines inside Canyonlands National Park are located in the Chinle Formation. The Chinle Formation dates from the Triassic Period (205.1 to 250 million years ago) and is made up of rock consisting of coarse sandstone, conglomerate, and limestone interbedded with varicolored shales of red, brown, purple, gray, and green. This formation weathers to a talus slope under the more resistant cliff- forming Wingate Formation. The Chinle Formation was stream- deposited as point bars and includes many fossil plants and animals. During the later Tertiary Period (about 70 million years ago), groundwater deposited uranium in some of these organic remains. Decay of organic material from the plant remains created micro- reducing environment, which caused the uranium to precipitate. Mineralization significantly postdates the deposition of the sediments, occurring during the Tertiary (Foos, 1999).

Wetlands

Wetlands stabilize stream banks, act as filters to improve water quality, attenuate flood waters, and enhance biodiversity (i.e., provide habitat for amphibians, reptiles, birds, including threatened and endangered species). Wetlands also are highly productive in terms of biomass and nutrient productivity, and are valuable water sources for wildlife and recreationists.

The potential for human impact on wetlands is great (Geoindicators scoping meeting, unpublished report, June 2002). Parking lots and structures in or near stream channels, structures in floodplains (e.g., culverts and bridges), grazing in uplands and stream channels, roads and trails in streambeds, introduction of exotic species, and flow regulation and diversion can all cause significant impacts to wetlands. Agricultural activities and past extirpation of beaver have also affected wetlands.

Recommendations
1. Inventory location, character, and conditions of wetlands in the park.
2. Inventory distribution of exotic species in wetlands.
3. Monitor groundwater levels and surface elevations.
4. Investigate age- structure of woody riparian plants in relation to land use.
5. Investigate linkages between amphibian parameters and wetland health.

Wind Erosion

Eolian (windblown) dust is important in desert ecosystems as a source of nutrients and as a substrate for biological soil crusts, which stabilize arid surfaces and cycle nitrogen. On the other hand, the presence of eolian dust in arid- land surficial deposits and soils renders these deposits vulnerable to wind erosion (Reynolds, 1999). Geologic and geochemical considerations imply dust transport over many tens of hundreds of miles, and magnetic and petrologic results confirm an eolian origin for much of the silt in Pleistocene and Holocene alluvial surfaces (Reynolds, 1999).

Wind is a major force that can redistribute soil resources (e.g., litter, organic matter, and nutrients), and sediment within and among ecosystems. Accelerated losses of soil and sediment by erosion can indicate degradation of arid- land ecosystems because ecosystem health is dependent on these resources. Investigators found that while undisturbed soil crusts are almost never impacted by typical winds found in these regions, disturbance of the soils left them vulnerable to wind erosion for up to 10 years. Examination of crustal microstructure showed that both biomass and photosynthetic activity was concentrated in the top (0.12 inches; 3 mm) of the soil surface, thereby potentially removing much of the cyanobacteria biomass concentrated there. As these crusts contribute substantial nitrogen and carbon to desert region, erosion of these surfaces can result in greatly reduced site productivity and fertility (Belnap and others, 1997).

Sand blowing across and accumulating on roads occasionally causes problems. More commonly, motorists using back roads should be cautious when proceeding into areas of sheet or dune sands. Loss of traction in sandy areas becomes more pronounced during the hot summer months when even gentle slopes of sand cannot be traversed in a motor vehicle (Doelling and others, 1994).

Wind erosion and deposition of dust and sand can be accelerated by human activities. Trampling and vegetation alteration by livestock, and human recreational activities (e.g., hiking, biking, and driving, especially off established trails and roads) can destabilize soils and increase soil susceptibility to wind erosion. Some localized heavy visitation areas have seen crust death by burial from windblown sands when nearby crusts have been trampled (Geoindicators scoping meeting, unpublished report, June 2002). In addition, wind erosion and sediment transport may be strongly impacted by land- use practices outside the park. Eolian sand from disturbed surfaces may move via saltation onto undisturbed ground, burying and killing vegetation or biological soil crusts, or breaking biological soil crusts to expose more soil to erosion. Because park management practices limit or prohibit off- road travel, human impacts within the parks are associated primarily with off- trail hiking in high- use areas.

Recommendations
1. Monitor movement of soils and sediments. Some data are available from the Needles district (Geoindicators scoping meeting, unpublished report, June 2002).
2. Investigate ecosystem consequences of movement of soils and sediment.
3. Investigate natural range of variability of soil and sediment movement in relation to landscape configuration and characteristics.

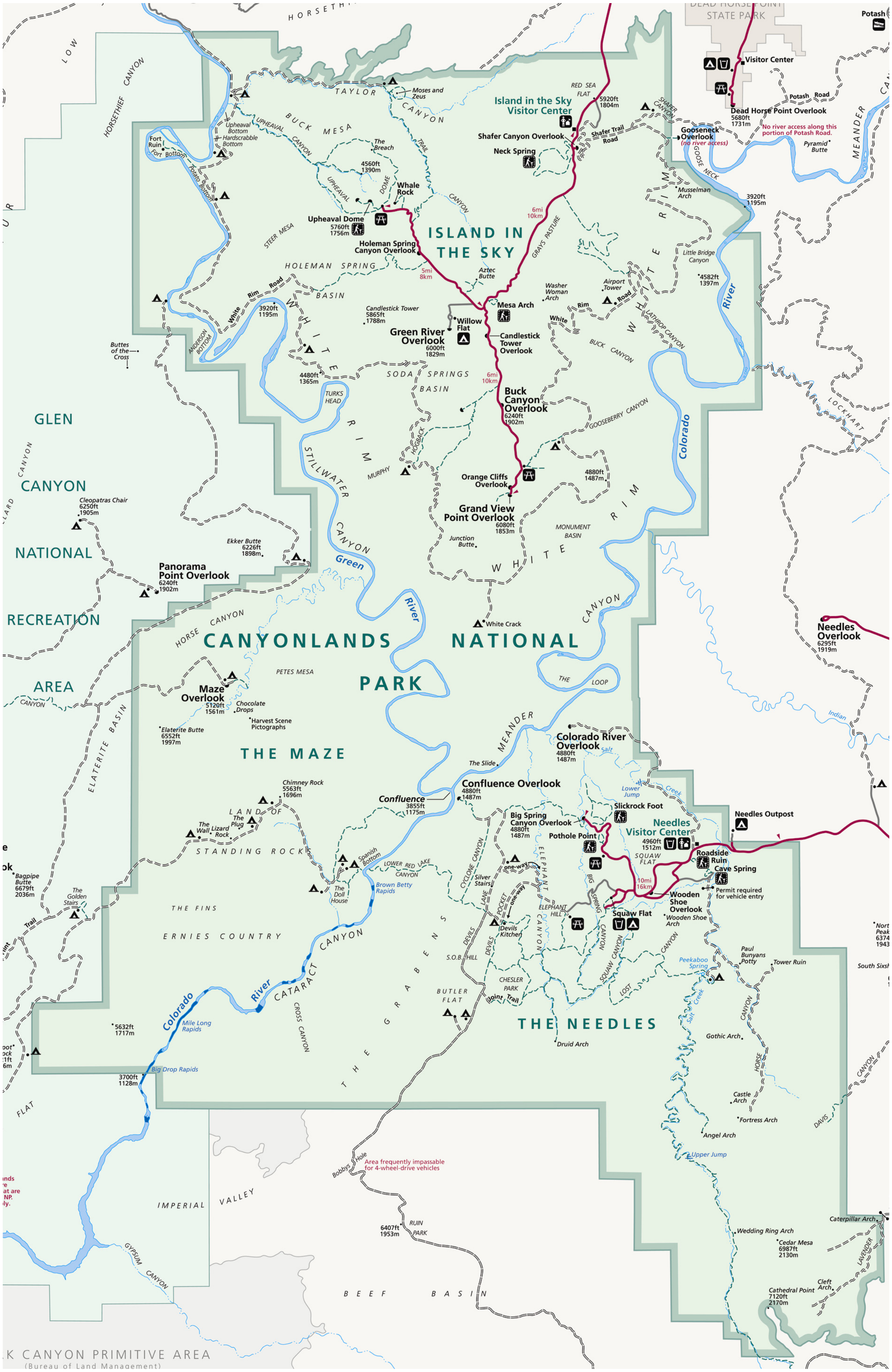

Figure 2. Generalized map of Canyonlands National Park.

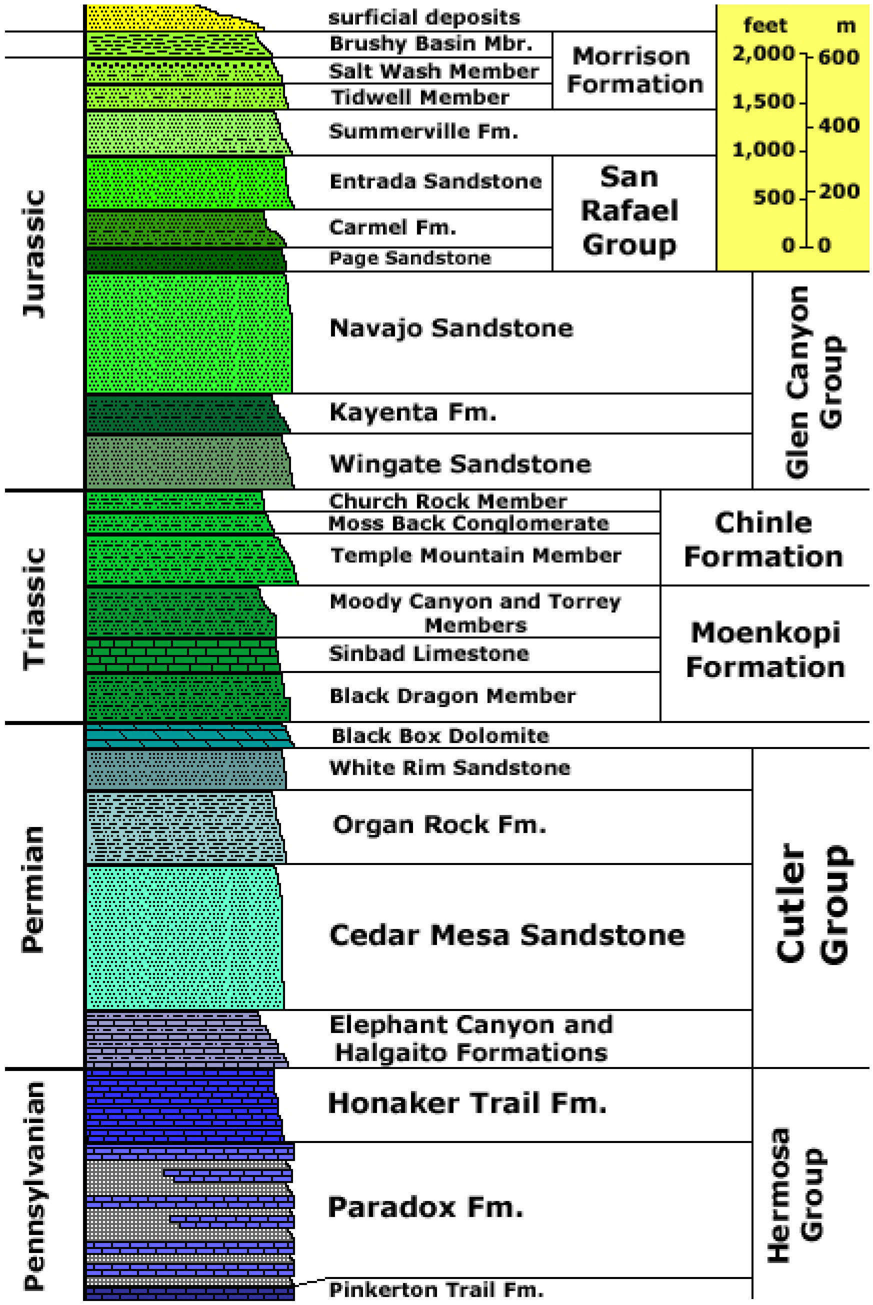

Figure 3. Generalized Stratigraphic Column for Canyonlands National Park. This figure shows the rock units discussed in this report. *Source*: USGS (http://3dparks.wr.usgs.gov/coloradoplateau/canyonlands_strat.htm).

Geologic Features and Processes

This section provides descriptions of the most prominent and distinctive geologic features and processes in Canyonlands National Park.

The magnificent scenery, character, and beauty of Canyonlands National Park are the result of geologic processes, including erosion and mass wasting. In addition, structural features, seen at the surface today, result from Laramide and younger rejuvenation of preexisting fracture patterns of Precambrian age. These features are complicated by the presence of salt of the Middle Pennsylvanian Paradox Formation at shallow depth.

Colorado (or Cataract) Lineament

According to Baars (2000), an important northeast-trending fault zone underlies the general course of the Colorado River from near Grand Junction, Colorado, to eastern Grand Canyon. Case and Joesting (1972) recognized the basement fault zone as a result of geophysical studies of the region by the U.S. Geological Survey. They called it the "Colorado lineament" for its position beneath the general course of the river. Later, Warner (1978) included the basement fault with numerous other northeasterly basement faults that occur in a broad band some 50 miles (80 km) wide, and called the entire fault zone the "Colorado lineament." Because of the possible confusion resulting from these designations, Stevenson and Baars (1987) renamed the feature the "Cataract lineament." Regardless of the name, in a general way the Colorado River follows the fractured zone in surface rocks above the basement fault zone across Canyonlands. In search for suitable waste disposal sites in the Paradox basin, Wong and others (1987) documented minor recurrent seismic activity along the basement fracture zone in their study of earthquake activity along the Meander anticline.

Colorado and Green Rivers

The Colorado River flows through an impressive string of outstanding National Park System areas: starting in the high country of Rocky Mountain National Park (Colorado) then flowing past Colorado National Monument (Colorado) to Canyonlands where it joins the Green River. Below Canyonlands, the river flows through the Glen Canyon National Recreation Area (Utah), which extends some 115 miles (185 km) downstream through Lake Powell to Glen Canyon Dam in Arizona. From there it runs through Grand Canyon National Park (Arizona) and into Lake Mead National Recreation Area (Nevada).

In Canyonlands, the Colorado River flows south through a spectacular, deep, narrow- walled gorge, where it is joined by its largest tributary, the Green River, which also has a deep narrow canyon. Together they flow for about 3 miles (5 km) through a generally rapid- free reach until they enter Cataract Canyon at Spanish Bottom. The turbulent water in Cataract Canyon, which flows at a rate of around 40 million gallons (151,400,000 L) per minute, is largely "white water." Changes in the stream channel's bedrock, slumping of the lower beds in the canyon walls, and blocks of rock falling from the cliffs into the stream create the rapids.

The Colorado River follows a course through Cataract Canyon along the edge of a basement faulted zone (see Colorado Lineament, this section). The large faults on the east wall of the canyon do not appear on the west wall—nor do the intricate fracture patterns in the rocks on the southeast side of the river like the lines of needles and their intervening, north- south "racetrack" valleys across the river (Harris and Tuttle, 1990).

The bed loads of both the Green and Colorado Rivers are extremely abrasive, a significant factor in their ability to cut channels and form incised (or entrenchment) meanders (see "Entrenchment Meanders," this section). These two rivers have meandered back and forth on a fairly low, flat surface in the geologic past, and may have retained their meandering pattern as the region was uplifted. However, some geologists believe that during uplift (see "Late Cenozoic Uplift," this section), as base level lowered, the streams began downcutting their floodplains so rapidly by headward erosion that they could do very little lateral eroding (Harris and Tuttle, 1990).

The water in the Green and Colorado Rivers is not potable at Canyonlands because of the saline groundwater that seeps into the rivers from the underlying salt beds (see "Salt Beds," this section). People and animals in the park use water in potholes (see "Erosional Landforms," this section) in the White River Sandstone and Cedar Mesa Sandstone or depend on groundwater from seeps and springs along the contacts between the Organ Rock Shale and the White Rim Sandstone.

Desert Colors

An often- asked question is: why are the rocks in Canyonlands red? Various oxides of iron, some including water, produce not only brick red but also pink, salmon, brown, buff, yellow, and even green or bluish green that contribute to the varicolored rocks in the park. This does not imply that the rocks could be considered as sources of iron ore because the merest traces of iron, generally only 1 to 3%, is enough to produce even the darkest shades of red. The only rocks in the park that contain virtually no iron are white sandstones (i.e., the White Rim Sandstone Member of the Cutler Formation and Navajo Sandstone) (Lohman, 1974).

Microscopic examination of colored grains of quartz and other minerals shows the pigment to be a thin coating on and between white or colorless particles. Sand or silt particles weathered from such rocks soon lose their color by the scouring action of wind (see "Wind Erosion," this section) or water, so most of the sand dunes and sand bars are white or nearly so (Lohman, 1974).

Another type of coating on rocks is desert varnish, which is lustrous and smooth, and ranges in color from light brown to black, depending on how much has accumulated. Desert varnish forms on all types of surfaces, from pebbles to canyon walls, though it seems to form best on harder rocks with high silica content. Varnish is thicker and darker on the upper surfaces of pebbles and on rock walls facing the sun; therefore, high temperatures from exposure seem to be helpful for providing a good "tan" of desert varnish. In addition, observations after storms indicate that water is necessary to the formation of desert varnish: the dark stripes on canyon walls are the areas that are wetted by downward moving films of water. Desert varnish consists of clay (up to about 70%) and iron and manganese oxide (up to about 30%), often with some silica (Wyckoff, 1999). Many observers think that the "varnish" gets splashed or dripped onto rocks during storms, and as the water evaporates, the mineral matter stays behind, little by little forming a smooth coat. Other observers interpret dust as playing a role. Additionally, bacteria living on the hot rock surfaces may concentrate the necessary minerals and ensure that they are not washed away or dissolved (Stokes, 1969).

Prehistoric peoples (Fremont Culture or Anasazis) used desert varnish to make pictures on rocks by scratching through the coating to the lighter- colored, unweathered rock underneath (Harris and Tuttle, 1990). Pictographs by these early people can be seen in numerous places throughout the park.

Elaterite

In Elaterite basin along the park's western boundary, the White Rim Sandstone displays a "fossil" offshore bar that may have been a barrier island late in Permian time. This structure contains petroleum that seeps out of hydrocarbon source rocks as a dark- brown, tarry substance called "elaterite." This oil probably migrated into the sandstone and became trapped by the impermeable red shale beds along the east side of the sandbar. Because the structure has been exhumed by erosion and the gas has escaped, the oil is not recoverable (Harris and Tuttle, 1990).

Entrenchment Meanders

A peculiar feature along the Colorado and Green Rivers (best illustrated on a park map or seen at Dead Horse Point) is the anomalous tight meander bends enclosed by deep canyons. Typically, meanders are features found in more gently flowing rivers on broad floodplains. Entrenchment meanders in an area where the river descends steeply downstream in canyons seem contradictory. The likely explanation is that the meanders are at least partly inherited from ancestral streams that flowed across the area before the most recent uplift (Harden, 1990). Rivers perhaps established their meanders when thick, relatively weak Tertiary- age strata still covered the area. When erosion lowered the streambeds to the base of the Tertiary sediments, some of the stream sediments continued to maintain their meander pattern and erode their way into the resistant Mesozoic and Paleozoic strata forming entrenchment meanders. The stream's energy, supplied by increased velocity, cut its channel deeper but could not widen it until encountering a zone of weak or easily erodible rock, such as at Spanish Bottom, where gypsum beds have been eroded (Harris and Tuttle, 1990).

Just as river meanders experience cutoff when water flows across narrow necks of land in unconsolidated basins, so do entrenched meanders experience cutoffs as rock walls separating nearby channel segments are eventually worn away—enabling the stream to take a short cut. The abandoned river channel is called a "rincon" in the southwestern United States and is analogous to an abandoned oxbow in a meandering stream (Kiver and Harris, 1999).

Erosional Landforms

Alcoves and Caves

Alcoves and caves in sandstone form through differential weathering along shale- sandstone contacts. Massive, cliff- forming sandstone can contain soft, erodible beds of shale. Water readily percolates down through sandstone but is trapped and cannot pass through shale beds because their pore spaces are so small. The groundwater is forced to move laterally along the contact between the two rock units until it seeps out on the face of the canyon wall or at the back of an alcove, creating a spring or seep. The prolonged flow of water along these spring and seep zones ultimately dissolves calcium- carbonate cement and loosens individual sand particles and blocks of sandstone, thus forming a void that enlarges with time.

Arches

The formation of natural arches begins with a narrow wall through which an opening appears. Parallel, smooth- walled cracks—joints—that cut steeply inward through rock create these thin walls of rock (Stokes, 1969). Joints provide passageways for water and roots and tend to form wider cracks as erosion progresses. If two joints grow and widen within a few feet or yards of each other, the thin wall of stone that is necessary for the formation of an arch (or window) will be present. If the narrow wall is exposed to weathering, formation of an arch is even more favorable. If these conditions are met, the wall may be broken through before it wears away entirely. This opening may be widened or lengthened rather easily because erosion can now work on all exposed edges with gravity helping the process.

It is not an accident that nearby Arches National Park has extensive jointing, with literally thousands of parallel cracks that ultimately form arches and other unusual rock formations (Stokes, 1969). In Arches, the upper part of the sandstone is generally harder than the lower part, so arches form in profusion because perforating the lower part is comparatively easy. More than 300 arches have developed in the Jurassic Entrada Sandstone in Arches National Park. Canyonlands has 25 arches, mostly sculpted in Permian Cutler Group sandstone, which is actually more likely to form standing rocks (see "Monuments," this section) than arches (Harris and Tuttle, 1990). Nevertheless, outstanding examples, such as Angel Arch and Druid Arch, occur within Canyonlands National Park.

Natural arches, some of the distinctive landmarks in the Needles district, may form from fins (see "Fins," this section). As the joint spaces widen and deepen, beds at the base of the fins are exposed. If the lower beds are slightly softer, they are removed more rapidly than the higher beds. Because the fins are narrow, a hole (or window) appears where the rock is worn completely through. Sand blown by wind (sand blasting) polishes and rounds off the window edges (see "Wind Erosion," this section). Snow, rain, and ice continue to attack the rock, dislodge fragments, and cause rockfalls until a window is enlarged to form a natural arch (Harris and Tuttle, 1990).

Buttes and Mesas

Buttes and mesas stand isolated on broad, nearly level terrains, far from valley walls. Buttes are generally higher than wide; mesas, wider than high. One definition says a feature is a butte if its top surface covers less that a square mile; if more, it is a mesa. Mesas and buttes may be remnants of divides mostly eroded away (Wyckoff, 1999). When a butte becomes very slender with practically no area on its top, it may be called a monument of spire (Stokes, 1969) (see "Erosional Landforms," this section).

A mesa provides a perfect example of hard rock being undermined by less resistant softer rock underneath. The cap or top of a mesa may be one of several hard types of rock such as sandstone or basalt. Strangely enough, it also may be nothing more than gravel, which we might not ordinarily consider to be a "hard rock" (Stokes, 1969).

Since there are great numbers of alternating sandstone and shale beds in the Southwest, conditions are favorable for mesas to form with caps of sandstones and bases of shale. These common types may cover hundreds of square miles, such as Mesa Verde in southwestern Colorado, or they may be only a few acres in extent. They are flat on top because the capping layers are still in the relatively horizontal position in which they were laid down and because erosion has removed the softer rocks that were once above the cap rock. The "rim" which surrounds the level surface may be high or low depending on the thickness of the protecting bed. If the rim is high, it may not be easy to cross or climb. The slopes around a mesa are almost always covered with blocks broken from the rims, which proves that mesas, like other high- standing features, get smaller and eventually disappear (Stokes, 1969).

A large proportion of mesas are capped by hard layers of sandstone or conglomerate. A hard layer is essential but at one time an overlying soft layer, which forms the slopes and most of the mesa itself, was probably present. The arrangement of alternating hard and soft layers is common enough in the great piles of sedimentary rocks that exist, and only erosion is required to carve them into final form. A mesa does not start as a mesa, it begins to emerge when a succession of hard and soft layers is cut into by a river or exposed by faulting. Then the etching out of the hard layer by the stripping away of surrounding material begins. Soon a bench or terrace is formed as the surface on top of the hard layer gets wider and wider. This cliff surface is still attached to the canyon wall. Erosion wears away the projecting shelf or terrace so that a number of points or headlands begin to protrude. These are free on two or three sides, and eventually the remaining side is cut through to create a true mesa.

Canyons

Landslides, rockfalls, debris flows, and flash floods all play roles in canyon formation by causing canyon walls to recede. All of these processes are active within Cataract Canyon in Canyonlands National Park. The rocks of the inner gorge are very hard and resist the widening processes. The massive Cedar Mesa Sandstone caps the canyon rim, but softer rocks above the Cedar Mesa—the Organ Rock, Moenkopi, and Chinle Formations—have been eroded back for 5 to 15 miles (8 to 24 km) from the inner canyon to the prominent Wingate- Kayenta cliffs beyond. The sharp inner canyons are being cut into older, much more resistant limestones, where canyon- widening processes are very slow in comparison (Baars, 1993).

The forms of canyons vary from sharp V- shaped to straight- walled slits. Others have step- like sides, with slopes and cliffs alternating upward towards the edge or "rim rock." The reason for these differences lies in alternating soft and hard layers.

The Grand Canyon is the world's best example of the stair- step type of canyon, but there are hundreds of others formed wherever the sides are made of alternating hard and soft layers. Another good place to view step-like river sides is from Dead Horse Point near Moab, Utah.

Narrow "slot" canyons have vertical or even overhanging walls, formed in harder rocks that are of the same composition from top to bottom. There are no steps in the walls and are extremely hazardous for park visitors during cloudburst storms and flash floods. This type of canyon is cut chiefly by the stream that runs through the canyon. Rapidly flowing water in slot canyons carries grains of sand and larger rocks of all sizes and literally wears its way downward through the rock. Since there is no opportunity to undermine one part of the canyon wall more than another, the canyon remains narrow and of uniform width as erosion progresses.

Box canyons form when a major stream cuts down faster than its tributaries. Somewhere along its course the side walls of a box canyon abruptly close and an impassable wall is formed. The streambed continues upstream on a higher level, and any water running over the cliff creates a temporary waterfall. Since tributaries cannot keep up with the downcutting stream, they lag behind and enter it by falling from a higher level. However, the tributary can cut backward away from the major stream so that the original fall or step moves away to form short, high-walled, box- like canyons.

Cliff- vs. Slope-Forming Rocks

Differences in the composition, hardness, distribution, and thickness of rock layers determine their ability to withstand the forces of fracturing and erosion and hence their tendency to form cliffs, ledges, or slopes (table 2). Most of the cliff- or ledge- forming rocks are sandstones consisting of sand grains deposited by wind of water and later cemented together by silica (SiO_2), calcium carbonate ($CaCO_3$), or one of the iron oxides (such as Fe_2O_3). Some hard, resistant ledges are made of limestone (calcium carbonate).

The nearly vertical cliffs supporting the highest mesas consist of the well- cemented Wingate Sandstone protected above by the even harder sandstone of the Kayenta Formation. Even a few feet of the Kayenta protect the rock beneath (Lohman, 1965). In some places, remnants of the overlying Navajo Sandstone make up the topmost unit of cliffs.

Table 2. Erosional forms of rocks in Canyonlands National Park

Age	Rock name	Erosional forms
Triassic	Navajo Sandstone	Forms residual rounded patches on highest mesas; sometimes makes up topmost unit of cliffs
Triassic	Kayenta Formation	Caps most high mesas and tops of highest cliffs
Triassic	Wingate Sandstone	Forms highest cliffs (many of which are coated with desert varnish)
Triassic	Chinle Formation	Forms steep slopes at bases of highest cliffs
Triassic	Moenkopi Formation	Forms slopes broken by thin ledges
Permian	Cutler Group	Forms needles, arches, and other erosional features
Permian	Honaker Trail Formation	Forms steep canyon walls

Source: Lohman (1974).

Fins

The Fins in the Maze district are narrow sandstone ridges, or walls, that are eroding along parallel joints. Cracks between closely spaced vertical joints become enlarged by chemical and physical weathering as water seeps down, dissolving iron- oxide cement and loosening sand grains. Frost action, with its alternate freezing, expanding, and thawing, also breaks up sandstone. Loose sediment is removed by wind and runoff. The joint spaces gradually enlarge into narrow valleys that separate the narrow wall, called fins (Harris and Tuttle, 1990).

Monuments

The east side of the Colorado River is an area of great diversity, including color and forms (e.g., spires, columns, needles, and toadstool pedestals). The Needles themselves are similar to fins but have more crisscross fractures. Needles, like fins, are the result of weathering and erosion along joint and fault lines, some of which are quite close together, a feature characteristic of the Cedar Mesa Sandstone. The Joint Trail, which goes through a crack in this formation, is only a couple of feet wide.

Needles and pillars develop when two intersecting joint sets are spaced closely together. The second set of joints, which is at an angle to the first set, prevents fins from developing. Instead, pointed needles or rounded pillars evolve as weathering and erosion sculpt the rock. Some pillars are capped by resistant material that makes balancing rocks. Where fins have developed, they tend to evolve into a line of pillars as weathering attacks cross joints (Harris and Tuttle, 1990).

Potholes and Tanks

Potholes form in the Cedar Mesa Sandstone because calcium carbonate that cements its sand grains is soluble in natural carbonic acid (carbon dioxide plus water). Carbonic acid attacks any weak spot or zone in the sandstone. Loosened sand grains fall and are washed or blown away. Once a slight depression is started, more and more of the sandstone is exposed to the processes of weathering and erosion. Potholes, caves, and sometimes arches develop in this way (Harris and Tuttle, 1990). Paul Bunyan's Potty is a well know example.

The hollows where water collects—locally referred to as "tanks" or "charcos"—are formed by the combined process of solution of calcium carbonate cement and the removal of loose rock grains by wind (deflation). Tanks are found by Junction Butte near Grand View Point in the central portion of the park and also in the Needles district near Chesler Park (Harris and Tuttle, 1990).

The Grabens

The Grabens, which parallel Cataract Canyon, is an area of elongate collapse valleys including a series of arcuate fault blocks. Great thicknesses of salt accumulated in subsiding, elongate, down- faulted valleys parallel to the rising, up- faulted ranges of the Uncompahgre uplift. As the weight of sedimentary overburden (washed down from the mountains) became ever greater, the salt began to flow toward the southwest, away from the source and greatest weight of sediment. When the flowing salt came against the fault- block ridges, it was deflected upward, forming salt walls and plugs that penetrated the overlying beds. In this way, the salt took the path of least resistance to reach areas where the pressure of overburden was lower (Harris and Tuttle, 1990).

The underlying salt deposits of the Paradox Formation acted as an unstable platform for the millions of tons of overlying shales and sandstones. The rocks here are on the northwest flank of the Monument upwarp and are gently inclined about 4° toward the Colorado River. When the river cut through the sandstone layers into the mechanically weak mudstone and evaporite layers below, the lateral support for the brittle sandstone layers was removed. The brittle sandstone slowly glided toward Cataract Canyon on top of the evaporite layers below, breaking into a series of parallel fault blocks. Groundwater slowly dissolved the evaporite minerals further encouraging collapse, lateral sliding, and faulting of the sandstones. The process is very recent and began perhaps 300,000–500,000 years ago when Cataract Canyon was deep enough to remove lateral support. Thus, collapse and lateral movement of the brittle block formed the unique structures and topography of The Grabens (Kiver and Harris, 1999).

Fault scarps along the sides of The Grabens are untouched by weathering and erosion; moreover, streams have not had sufficient time to completely adjust to the newly formed fault- block topography and often flow into depressions lacking outlets. The process continues today as the newest tensional fault is producing "baby graben" near Devil's Kitchen. As the rock continues to split and crack, loose soil and desert plants fall into the opening abyss—about 40 feet (12 m) deep. Another indicator that salt is still being dissolved is that river water in and downstream from Cataract Canyon is undrinkable because of the high salt content (Kiver and Harris, 1999).

Groundwater

Three groundwater regimes are present in the vicinity of Canyonlands National Park. The first involves bedrock aquifers and aquicludes above the level of the Moenkopi Formation, the second involves those below the Moenkopi or the deep groundwater regime, and the third involves unconsolidated units.

Bedrock Aquifers above the Moenkopi Formation

Aquifers of the first regime are isolated from significant recharge by the deep canyons of the Colorado and Green Rivers. Even though excellent aquifers are present, discharge from springs is small, and wells are expected to have small yields because of low discharge. Snow accumulating and melting on the warped tableland provides the only significant, but limited, recharge to the upper aquifers. Precipitation varies annually, but averages 8–10 inches (20–25 cm) per year (Doelling and others, 1994).

The best groundwater aquifers include Wingate Sandstone, Navajo Sandstone, and the Moab and Slick Rock Members of the Entrada Sandstone. Springs issue locally from all of these units. Most of these units are replete with joints and fractures, which favors recharge. These springs rarely produce more than 10 gallons per minute (37.8 L/min), but are adequate for livestock (Doelling and Morgan, 2000).

Deep Groundwater Regime

The deep groundwater regime may be subdivided into three hydrostratigraphic units (U.S. Department of Energy, 1984). The upper unit consists of Permian rocks and the upper two- thirds of the Pennsylvanian Honaker Trail Formation. The middle unit includes the remainder of the Honaker Trail Formation and the Paradox Formation. The lower unit includes all the carbonate units below the Paradox Formation. The recharge area for the upper unit probably includes the La Sal and Abajo Mountains. The transmissivity of the upper hydrostratigraphic unit is largely unknown and untested, but permeabilities of Permian strata are low and largely controlled by the presence of local faults and joints (Huntoon, 1985). The amount of water is expected to be small and probably not good in quality. Known seeps in the Permian Cutler Formation are from perched waters and are largely salty and not potable (Huntoon, 1977). Permian and Pennsylvanian strata below the level of the Colorado River are generally saturated with sodium-chloride brines in the Potash amphitheater area. The middle unit consists of horizons acting as aquicludes alternating with horizons of variable water- bearing capacity. Where water is found, it is generally very salty (Doelling and others, 1994).

The lower hydrostratigraphic unit consists of carbonates with good porosity and permeability. Oil- well data generally indicate large quantities of salty, connate water. The saltiness may reflect original seawater or mixing with the middle hydrostratigraphic unit salines. Factors that control permeabilities, listed in order of decreasing importance, include faults, joints and bedding planes, intergranular porosity, and intercrystalline porosity (Huntoon, 1977).

Unconsolidated Aquifers

Water also may be present in surficial deposits that overlie bedrock discharge areas (Doelling and Morgan, 2000). The larger, unconsolidated sand patches that fill the hollows on the plateau offer opportunity for groundwater development above the cliffs. Yields are expected to be small, but possibly enough for watering livestock. Wells with larger yields might be developed in the Colorado River alluvium (Doelling and others, 1994). Phreatophytes, such as willow and tamarisk, generally grow in profusion in areas of shallow groundwater where discharge from springs occurs (Doelling and Morgan, 2000).

Laramide Orogeny

Many geologists working on the Colorado Plateau credit the origin of structures with the Laramide orogeny because, in general, that is what is seen at the surface. This interpretation, however, does not take into account what happened prior to this mountain- building event. Numerous geologists have shown that Precambrian structural basement fabric, which has been repeatedly rejuvenated throughout Phanerozoic time, directs the peculiar orientation of regional structures in the province, and that the Laramide orogeny merely rejuvenated and enhanced basement fault patterns (Baars, 2000).

The Laramide orogeny, the mountain- building event that closed out the Mesozoic Era and lasted into Tertiary time, elevated the Canyonlands region thousands of feet but left the sedimentary rock units essentially horizontal. The dip of the beds is so slight as to appear flat. However, the tectonic compressive forces that pushed up the surrounding mountains also produced (or rejuvenated) joint systems and fractures that strongly influenced patterns of landform development in Canyonlands. Erosional processes, intensified by uplift, tended to follow the joint patterns while dissecting the flat- lying rocks.

Late Cenozoic Uplift

The Colorado Plateau serves as a classic example of the interaction between uplift and erosion. The region was at sea level during the Late Cretaceous, but now the deeply eroded land surface is at about 1.2 miles (2 km) in elevation. The path of the landscape between these two endpoints is not clear, however, and geologists have long debated the mechanisms, amounts, and timing of uplift and erosion.

Recent studies using geographic information system (GIS) to map, interpolate, and calculate rock uplift and erosional exhumation of the Colorado Plateau during the Cenozoic Era provide insight into the landscape's development through time (Pederson and others, 2002). Initial results indicate uplift and erosion are highly spatially variable with mean values of 6,946 feet (2,117 m) for rock uplift and 1,332 feet (406 m) for net erosional exhumation since the Late Cretaceous coastal sandstones were deposited. Investigators estimate 2,766 feet (843 m) of erosion since 30 million years ago, which can account for 2,096 feet (639 m) of post- Laramide rock uplift by isostatic processes.

Based on initial results, investigators suggest two end-member scenarios for uplift of the Colorado Plateau. First, all rock uplift on the Colorado Plateau has been provided by only about 1.2 miles (2 km) of Laramide uplift and subsequent erosional isostasy, with no other sources of later Cenozoic uplift. Second, proposed mantle sources of middle- late Cenozoic uplift are valid, but then with isostatic rebound from erosion included, Laramide uplift of the Colorado Plateau must be minor (less than 1,640 feet [500 m]).

In either scenario, Laramide uplift of the Colorado Plateau is much less than that in the neighboring Rocky Mountains, which may be expected considering the plateau contains the Unita, Piceance, and San Juan sedimentary basins that have subsided, not uplifted, since the Cretaceous. Ironically, the problem with the Colorado Plateau is that investigators have proposed sources for more uplift than there is actual uplift. Initial data from Pederson and others (2002) support a resolution wherein early Cenozoic events provided the bulk of uplift (by whatever mechanism) with little passive erosional isostasy in the later Cenozoic.

Paleontological Resources

Honaker Trail Formation

The Honaker Trail Formation is a very fossiliferous, Pennsylvanian- age limestone exposed in Canyonlands National Park. This unit contains rugose corals, bryozoans, brachiopods, gastropods, a few trilobites, and crinoids (Santucci, 2000).

Cedar Mesa Sandstone

A fossil- rich locality within the Permian Cedar Mesa Sandstone has been reported from the Indian Creek drainage just east of Canyonlands National Park (Stanesco and Campbell, 1989; Sumida and others, 1999). Cranial and vertebral remains identified as the temnospondyl amphibian *Eryops* were collected from within a petrified log jam. The logs at this locality have been identified as conifers and reach a few feet in diameter. This site was completely destroyed by vandalism in 1995 (Sumida and others, 1999). Some tracks in Permian Cedar Mesa Sandstone may exist in the park, accessible by river (Adrian Hunt, oral communication, 1998).

Moenkopi Formation

A few poorly preserved steinkerns and gastropods impressions were reported from the Lower Triassic Sinbad Limestone Member of the Moenkopi Formation in the park (Lucas, 1995). These specimens were first reported by McKnight (1940) and are dominated by the following taxa: the brachiopod *Lingula* sp., *Monotis thaynesiana*, unidentified viviparoid gastropods, and the ammonite *Meekoceras* sp. (Santucci, 2000).

Chinle Formation

The Upper Triassic Chinle Formation is well exposed in the park and contains diverse faunal, floral, and ichnofossil assemblages. Vertebrate body fossils reported from the park include the remains of semionotid and turseodid fish, metoposaurs, phytosaurs, and the aetosaur *Stagonolepis* (Hasiotis, 1993; Lucas and others, 1997; Heckert and others, 1999). Also, within this unit are fresh water gastropods, bivalves, conchostrachans, and the earliest known crayfish. An abundance of fossil plants occur in the Owl Rock Member of the Chinle Formation including *Neocalamites* sp. and *Pagiophyllum* sp.

Burrows produced by lungfish, crayfish, worms, and insects are common in the Chinle Formation in Canyonlands National Park (Hasiotis and Mitchell, 1989; Hasitotis, 1993, 1995). Hasiotis (1993) also reported a horseshoe- crab resting trace from the park. A single well- preserved impression of a tridactyl dinosaur footprint (*Grallator* sp.) was found in the Rock Pont Member of the Chinle Formation near Upheaval Dome (Hunt and others, 1993; Lucas and others, 1995). Another Chinle tracksite contains impressions of a tetrapod with four- toed manus (hand) and a five- toed pes (foot). These tracks have blunt toes, lack claw impressions, and have been identified as *Brachychirotherium* sp. There are also two types of large five- toed tracks. One set is associated with an aetosaur- like reptile and the other is attributed to a dicynodont reptile (Santucci and others, 1998).

Kayenta Formation

Fossil vertebrate tracks also are known from the upper part of the Kayenta Formation just below the overlying Navajo Sandstone in Canyonlands National Park (Lockley and Hunt, 1993; Santucci and others, 1998).

Salt Beds

The presence of the Paradox Formation's salt beds complicates fracturing and jointing in the Canyonlands area. Consequently, they affected the ways in which landforms evolved, especially in the northwestern and southeastern sections of the park. Sometime after uplift began, and as erosion stripped off the younger beds, groundwater began to reach the buried salt beds. Some of the upper salt layers were dissolved, but the less soluble gypsum was left in place. In places where salt dissolution occurred—as it was under the salt valleys and grabens—the overlying sedimentary beds collapsed.

Upheaval Dome

Upheaval Dome may be the most spectacular and intriguing topographic feature in Canyonlands National Park. Geologists have debated the origin of the distinctive structure for generations, and the controversy continues today. In the 1920s and 1930s, studies attributed its origin to various mechanisms: salt penetration (Harrison, 1927), cryptovolcanic activity (Bucher, 1936), and meteorite impact (Boone and Albritton, 1938). In the 1950s, scientists for the U.S. Geological Survey mapped the feature and interpreted it as a classic salt dome, which seemed a reasonable interpretation as salt occurs at depth regionally and other salt- intruded anticlines are in the vicinity of the park.

Then in the 1980s, the earlier notion of a meteorite impact resurfaced (Shoemaker and Herkenhoff, 1983, 1984). Additionally, papers published in 1999 and 2000 revealed the results of detailed mapping that showed convincing evidence of Upheaval Dome being an impact structure (Kreins and others, 1999) and interpreted seismic reflection data as favoring an impact origin (Kanbur and others, 2000). Investigators identified features within the images typical of impact structures. In addition, images show less than 30 feet (100 m) of relief in the Paradox Formation, which is contrary to salt diapirism hypotheses, and deformation occurring only above the Hermosa Formation (in the upper 262 feet [80 m] of the structure). The images also suggest limited fracturing of the Hermosa and salt flow in the Paradox Formation, perhaps due to gravitational relaxation of the crater form (Kanbur and others, 2000).

Also in the late 1990s, other geologists presented convincing data, again using detailed mapping, that the fracture patterns and continued growth of the structure, at least through Jurassic time, required long- term, continuous growth from salt rising from depth. To explain the lack of salt beneath the structure today, they postulate that the diaper flowed salt onto the surface in the Chinle Formation through Triassic (Navajo Sandstone) time, and then the salt blob was pinched off, the flowed salt having since been eroded away. Another mechanism to cause a salt pinch- off would be that the mother source of salt was depleted in the late development of the structure (Jackson and others, 1998).

Unconformities

Unconformities are "gaps in the rock record" during which time no rocks were deposited or subsequently were eroded away. Although none of the unconformities that occur in Canyonlands National Park rival the angular unconformity in Colorado National Monument to the east, the park has three unconformities worth noting.

First, a regional erosional (Pennsylvanian- Permian) unconformity occurs at the top of the Honaker Trail Formation that extends from Canyonlands northwestward onto the San Rafael Swell, and beyond. Some angular discordance occurs at the erosional surface near the confluence of the Green and Colorado Rivers in the heart of the park. As the unconformity is difficult to visualize from vertical air photos, some scientists have disputed its existence. Nevertheless, the widespread nature of the erosional surface and the distribution of the largely marine rock sequence above indicate that the rocks were deposited in a separate basin that formed to the northwest of the Paradox basin (Baars, 1987).

Second, an unconformity between the Paleozoic and Mesozoic (Permian and Triassic) beds represents withdrawal of seas and a lengthy period of erosion when the continent was relatively high. No rocks of Late Permian age are known to occur anywhere on the Colorado Plateau (Baars, 2000). The Colorado Plateau was left high and dry to the east and north of seaways at this time. Any continental sediment that may have been deposited on the plateau did not survive the severe erosion that formed the post- Permian regional unconformity (Baars, 2000).

The Triassic units in the Canyonlands area are red beds consisting of shallow- water clastic sediments deposited by streams throughout a broad lowland that sloped gently toward a western ocean. The red beds are truncated by an angular unconformity, apparently beneath the Triassic Moenkopi Formation—mudstones that accumulated on tidal flats. As the rippled bedding at the top of the Permian White Rim Sandstone is beautifully preserved, the red beds must have been deposited shortly after the sea withdrew to the west. The red beds are stripped from the top of the sand bars by the erosional surface. The relationships indicate that the red beds are of Permian age, and should not be considered basal Moenkopi (Baars, 2000).

Third, an unconformity separates Moenkopi beds from varicolored, overlying Chinle beds, which are mostly slope- forming shales. The top of the Moenkopi Formation is scarred by erosional features, especially channels, sometimes cut rather deeply into the upper surface. Stream sand and gravel of the Moss Back

Member of the Chinle Formation commonly fill in the paleotopography on the eroded surface throughout Canyonlands. Because of the sporadic nature of the erosional depressions, the distribution of the Moss Back Member is irregular and spotty (Baars, 2000).

Wind Erosion

The erosional capacity of wind is limited by a number of factors, and on a global scale it is a far less potent erosional agent than fluvial activity. Compared with water, air has a low density and viscosity so only very fine particles can be carried in suspension, except at very high wind speeds near the ground, and together with moisture it tends to bind surface particles and prevent them from being entrained by the wind. Consequently eolian activity is only effective in areas that lack a relatively complete vegetation cover and where the surface material dries out at least occasionally (Summerfield, 1991).

Blowing dust, however, can substantially sculpt rock over long periods; blowing sand is even more effective. Although material of sand size (0.01 to 0.25 inches [0.25 to 6.4 mm] in diameter) cannot be lifted except by very strong winds, sand is moved along the ground by creep and saltation, leaving depressions where it has been removed and piling up as ripples and dunes elsewhere. Even relatively fine sand grains are too heavy for all but very strong winds to lift more than a few feet. Thus the belief that mesas, natural arches, and other sizeable landforms have been created by natural "sandblasting" is incorrect. Experiments conducted in deserts indicate that maximum abrasion by blowing sand on level ground occurs at a height of between 6 and 10 inches (15 to 25 cm), and the highest reach of abrasion is 4 to 5 feet (1.2 to 1.5 m). High- standing rock can be significantly abraded only if sand particles have a gentle slope, or ramp, up which they can move in stages by a process called saltation. For the most part, natural sandblasting is limited to the base of cliffs, low outcrops, and scattered stones. For example, rocks lying on the ground can be pointed, fluted, and pitted by blowing sand. Over lengthy periods, however, wind can move enormous amounts of sand over long distances, leaving depressions behind and piling up sand against highlands (Wyckoff, 1999)

Map Unit Properties

This section provides a description for and identifies many characteristics of the map units that appear on the digital geologic map of Canyonlands National Park. The table is highly generalized and is provided for informational purposes only. Ground disturbing activities should not be permitted or denied on the basis of information contained in this table. More detailed unit descriptions can be found in the help files that accompany the digital geologic map or by contacting the NPS Geologic Resources Division.

This section provides readily available information about the rock formations and deposits in Canyonlands National Park, including age, unit name and symbol, significant features, depositional setting, resource potential, resistance to erosion and development potential. Names and map symbols used in the table are from Huntoon and others (1982). The descriptions and significant features were prepared using primarily Huntoon and others (1982), Billingsley and others (2002), and Baars (2000).

Geologic History

This section highlights the map units (i.e., rocks and unconsolidated deposits) that occur in Canyonlands National Park and puts them in a geologic context in terms of the environment in which they were deposited and the timing of geologic events that created the present landscape.

Canyonlands, Utah's largest national park, is a geologic wonderland of spires and mesas rising to more than 7,800 feet (2,377 m). A large triangular plateau, called Island in the Sky, stands high above the confluence of the Green and Colorado Rivers (fig. 4). In the heart of the park, the two rivers come together through deep, sheer-walled, meandering canyons; below their confluence is Cataract Canyon, a 14- mile (23- km) long stretch of white- water rapids that challenge the most daring river-runners in the world. The Maze, an almost inaccessible jumble of canyons, lies west of the rivers; beyond are the red towers and walls of Land of Standing Rocks. Upheaval Dome, a spectacular topographic feature located in Island in the Sky, exposes rings of colorful Mesozoic rocks. On the Colorado River's southeast side are the strange, sculpted landforms of the Needles district, a natural exhibit of arches, fins, spires, grabens, canyons, and potholes.

The oldest rocks exposed in Canyonlands National Park are the Paradox Formation in the bottom of Cataract Canyon. The exposures of gypsum and interbedded black shale are less soluble than the halite salt beds underneath Upheaval Dome and the Needles district. The thousands of feet of evaporites that make up the Paradox Formation began to accumulate in Middle Pennsylvanian time when the Paradox basin subsided and the Ancestral Rocky Mountains of western Colorado began to rise.

A widely accepted interpretation of the environmental setting during deposition of the Paradox Formation is that individual salt beds were formed in relatively deep, highly saline seawater. During highstands of sea level, normal marine water could enter the Paradox basin across the shallow structural margins of the basin, depositing widespread black shale beds. As sea level lowered, seawater in the basin stagnated and intense evaporation occurred in the highly arid climate. Brine formed at the surface of the stagnant sea and sank to the bottom as intense evaporation progressed. The resulting dense brine could not pass across the basin thresholds, as in- flowing seawater created a hydrodynamic barrier. In the closed basin, water escaped only by evaporation, and because the climate was hot and dry, water evaporated rapidly, concentrating salts and mineral matter in shallow lagoons.

Toward the end of Pennsylvanian time, a warm tropical sea spread over the region. About 1,500 feet (457 m) of fossiliferous limestone, shales, and sandstones blanketed the salt basin. These are the gray beds of the Honaker Trail Formation that crop out at lower elevations in the deep canyons of the park, especially along the Colorado River. The dominantly marine section contains numerous fossil brachiopods, crinoids, bryozoa, corals, pelecypods, and gastropods.

Presumably, the weight of the accumulating overburden caused the salt beds of the Paradox Formation to begin flowing plastically before the close of the Pennsylvanian Period, and this process continued throughout the Permian Period and well into Mesozoic time. The migration of salt beds had probably stopped by the end of the Jurassic Period.

Early in Permian time, advancing seas deposited the Halgaito Shale, which grades into the Elephant Canyon Formation, a rock unit deposited in coastal lowlands. Also during Permian time, the Uncompahgre Mountains to the east were being severely eroded. Sediments shed from of the mountains enlarged the alluvial fans that gradually filled the basin at the foot of the range. The material in the fans lithified into iron- rich, red, arkosic, sandstones that are mapped as "undivided" rock units of the Cutler Group.

Inter- fingering with the undivided Cutler red beds are layers of white Cedar Mesa Sandstone, also of the Cutler Group, which were deposited in a coastal environmental setting (e.g., shallow marine and eolian deposits). The facies change between these continental and marine rock units occurs as a 4- to 5- mile (6.4- to 8- km) wide belt across Canyonlands National Park from south of the Needles through the Maze and into the Elaterite basin along the park's western boundary. Many of Canyonlands' most dramatic and colorful rocks are in this area where the two depositional facies shifted back and forth.

Also part of the Cutler Group is the Organ Rock Shale—oxidized muds which were laid down over the white sands of the Cedar Mesa Sandstone. The Organ Rock beds make up brightly colored red, orange, and brown slopes that separate cliff- forming units above and below. The White Rim Sandstone that forms the striking cliffs between undivided Cutler Group and Organ Rock red beds includes ancient sand dunes and large marine sand bars.

An unconformity between Paleozoic and Mesozoic beds represents withdrawal of seas and a lengthy period of erosion when the continent was relatively high. The record of the Mesozoic Era in the Canyonlands area begins with Triassic- age red beds consisting of shallow-water, clastic sediments deposited by streams throughout a broad lowland that sloped gently toward a western ocean. Mudstones of the Moenkopi Formation, which accumulated on tidal mudflats, are exposed in the northern and western sections of the park.

An unconformity separated the Moenkopi beds from the varicolored, overlying Chinle Formation, which consists of mostly slope- forming shales. The Chinle beds have been described as showing up on canyon walls like “a brilliant ring of fire” (Baars, 1983). In some places, pieces of petrified wood from the Petrified Forest Member of the Chinle Formation have weathered out of cliffs and accumulated around the base of the slopes. Also, bentonite in the Moss Back Member of the Chinle Formation produces dangerous conditions when wet along roads and trails.

As the Triassic climate became drier, sand dunes migrated across the region, burying the rivers and their floodplains. The dunes became the Wingate Sandstone, which is several hundred feet thick throughout Canyonlands and extends nearly continuously for hundreds of miles. In Canyonlands, the prominent cliffs of the Wingate Sandstone, the cliffs and slopes of the Kayenta Formation, and the cliffs, knobs, and rounded monoliths of the Navajo Sandstone characterize the rocks of the Triassic- age Glen Canyon Group. Much of the beauty and uniqueness of the Colorado Plateau is due to these rock units, which are well exposed in Canyonlands National Park.

Rock units of the Jurassic- age San Rafael Group unconformably overlie the Glen Canyon Group in the Canyonlands area, mainly scattered patches east and west of the park. For example, the massive Entrada Sandstone forms vertical cliffs and hummocky knobs that can be seen as one approaches Canyonlands National Park (e.g., Monitor and Merrimac Buttes). However, erosion stripped off most of the San Rafael beds in this area, as well as younger Jurassic and Cretaceous rocks from the park.

The periods of cold and increased moisture that characterize Pleistocene climates on the Colorado Plateau greatly increased the dissection and deepening of canyons, especially the incising of the canyons of the Green and Colorado Rivers. Increased runoff from glaciers in the Rocky Mountains and other highlands drained by these streams augmented the volume of these two rivers. Some of the dune deposits, landslide deposits, alluvial fans, and terrace gravels accumulated—or at least began to form—during Pleistocene time. Uplift and erosion, which started in Tertiary time, continues today, though at a somewhat slower rate in Utah’s current drier climate.

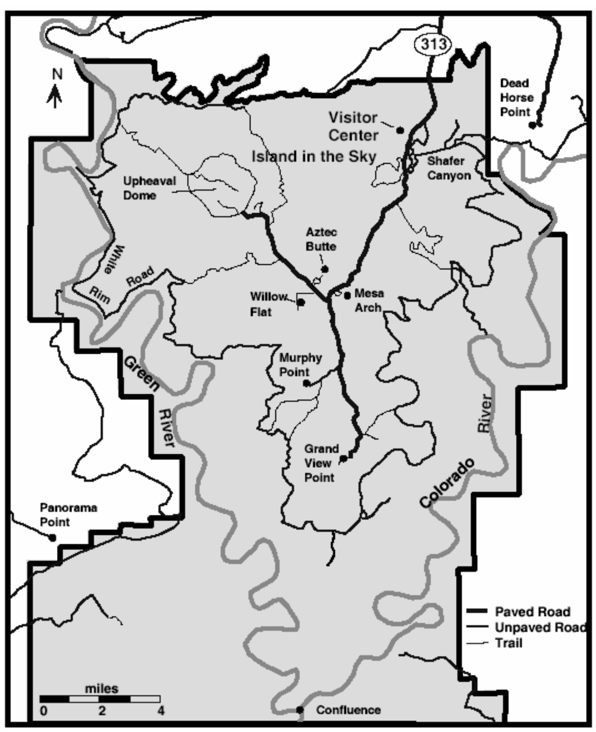

Figure 4. Map of the Northern Part of Canyonlands National Park. Among other geographic features, this figure shows Island in the Sky, a large triangular plateau that stands high above the confluence of the Green and Colorado Rivers.

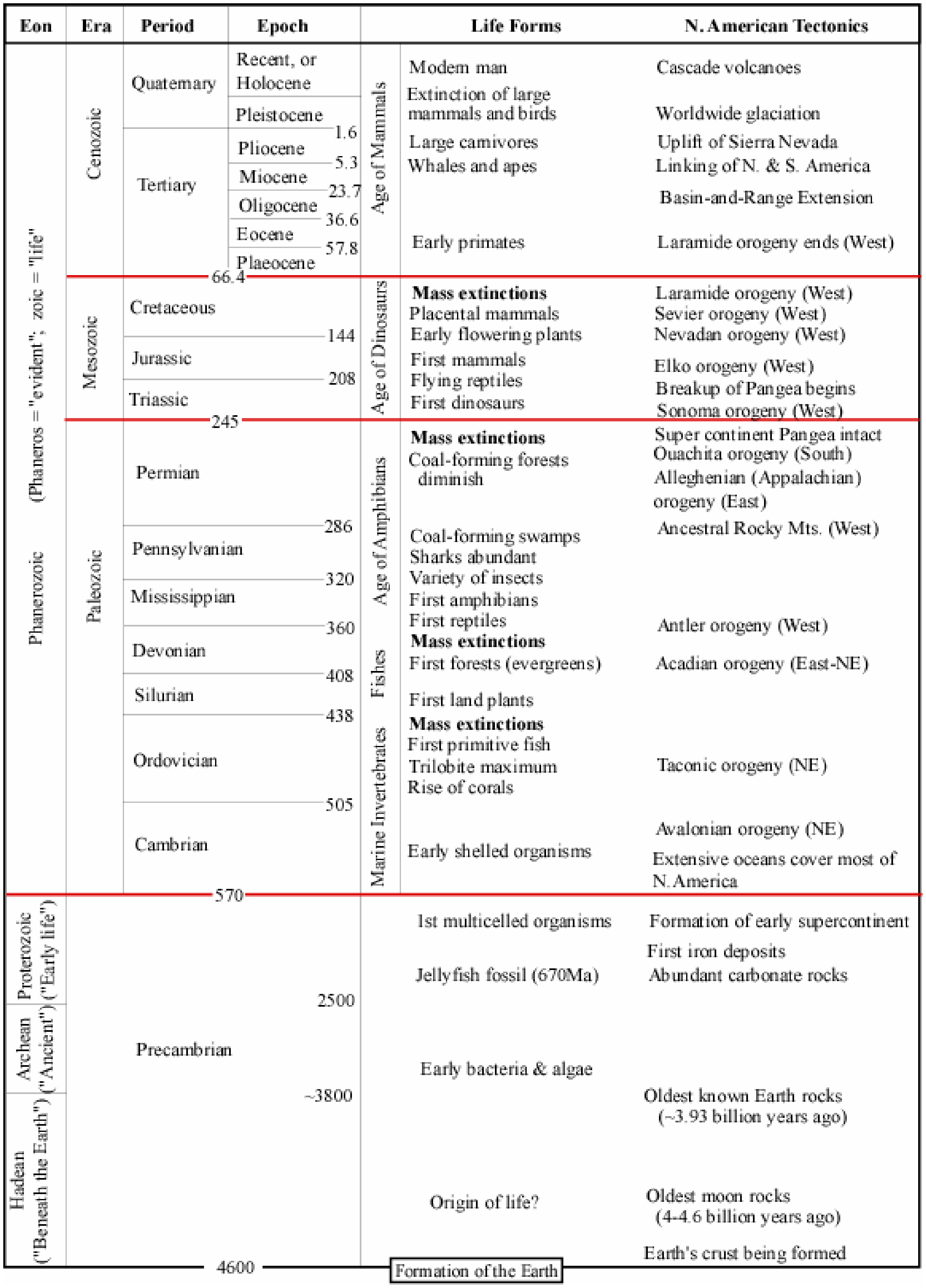

Figure 5: Geologic Time Scale - Red lines indicate major unconformities between eras. Included are major events in life history and tectonic events occurring North American continent. Absolute ages shown are in millions of years and are from the United States Geological Survey (USGS) time scale found at: http://geology.wr.usgs.gov/docs/usgsnps/gtime/timescale.html.

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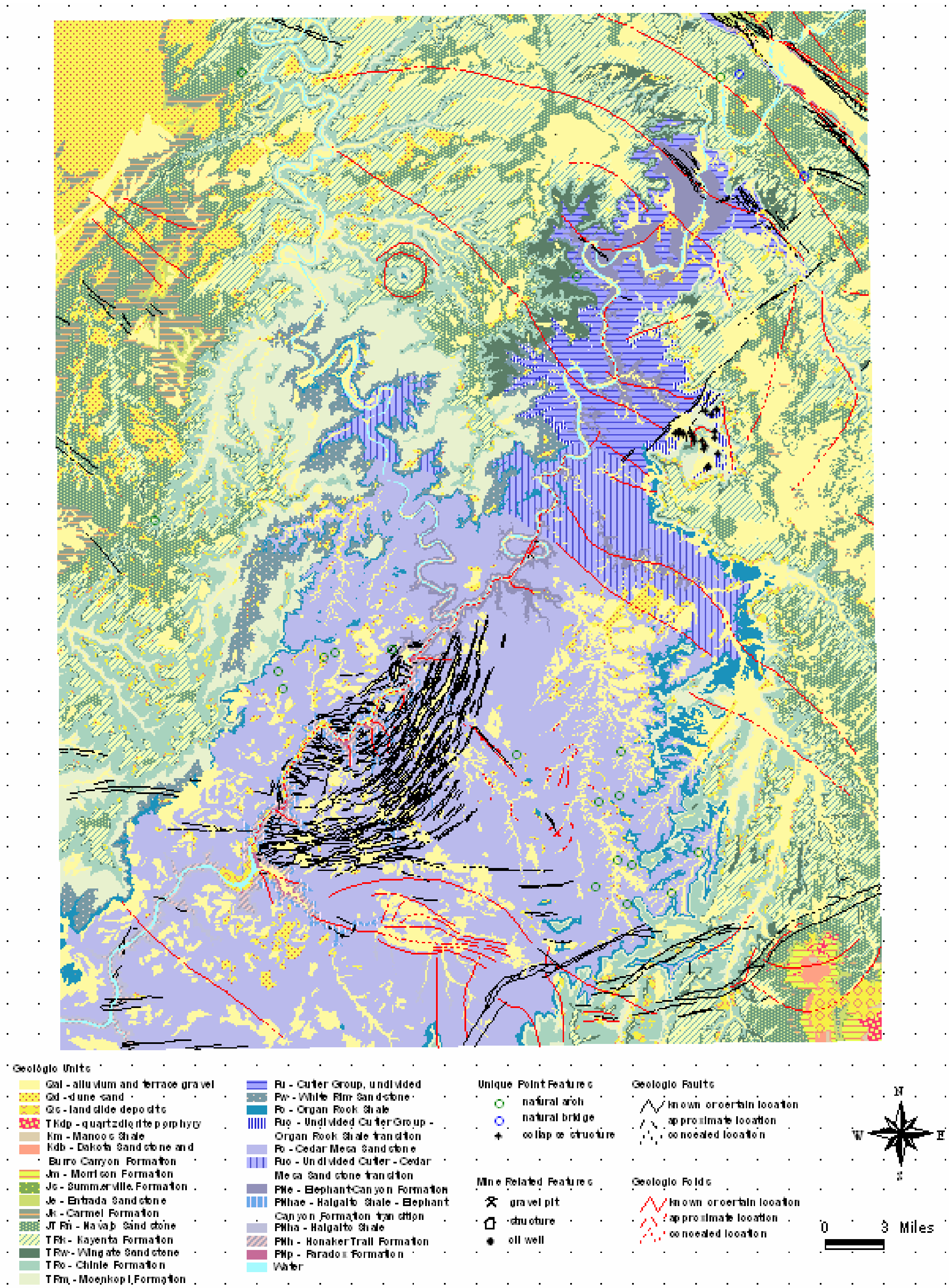
Appendix A: Geologic Map Graphic

This image provides a preview or "snapshot" of the geologic map for Canyonlands National Park. For a detailed digital geologic map, see included CD.



The original map digitized by NPS staff to create this product was: Billingsley, George H., Block, Debra L and Felgar, Tracey J., 2002, Surficial geologic map of The Loop and Druid Arch Quadrangles, Canyonlands National Park, Utah, U.S. Geological Survey, MF-2411, 1:24000 scale. For a detailed digital geologic map and cross sections, see included CD.

Appendix B: SEUG Scoping Summary

The following scoping summary highlights a workshop that was held for National Park System units in the Southeast Utah Group (SEUG) including Arches National Park, Canyonlands National Park, Hovenweep National Monument, and Natural Bridges National Monument from May 24–27, 1999

An inventory workshop was held for National Park System units in the Southeast Utah Group (SEUG) including Arches National Park, Canyonlands National Park, Hovenweep National Monument, and Natural Bridges National Monument from May 24–27, 1999, to view and discuss the geologic resources, address the status of geologic mapping by the Utah Geological Survey (UGS) for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), Natural Resources Information Division (NRID), Southeast Utah Group NPS staff (interpretation, natural resources, deputy superintendents), UGS, United States Geological Survey (USGS), and Utah Geological Association (UGA) were present for the two day workshop (See Attachment A).

Monday, May 24, involved a field trip to Natural Bridges National Monument (NABR) led by Red Rocks College geologist Jack Stanesco with additions from Christine Turner and Pete Peterson (both of the USGS).

Tuesday, May 25, involved a field trip to Canyonlands National Park (CANY) led by USGS geologist George Billingsley, again with additions from Christine Turner and Pete Peterson also of the USGS.

Wednesday, May 26, involved a field trip to Arches National Park (ARCH) led by UGS geologist Hellmut Doelling with additions from Grant Willis (UGS) and Vince Santucci (NPS- GRD).

Thursday, May 27, involved a scoping session to present overviews of the NPS Inventory and Monitoring (I&M) Program, the Geologic Resources Division, and the ongoing Geologic Resources Inventory (GRI) for Colorado and Utah. Round table discussions involving geologic issues for the Southeast Utah Group included interpretation, the UGA Millennium 2000 guidebook featuring the geology of Utah's National and State parks, paleontological resources, the status of cooperative geologic mapping efforts, sources of available data, geologic hazards, potential future research topics, and action items generated from this meeting.

Overview of Geologic Resources Inventory

After introductions by the participants, Joe Gregson (NPS- NRID) presented an overview of the NPS I&M Program, the status of the natural resource inventories, and the geological resources inventory.

The NPS geologic resources inventory is a collaborative effort of the NPS Geologic Resources Division (GRD) and Inventory and Monitoring Program (I&M) with assistance from the U.S. Geological Survey (USGS), American Association of State Geologists (AASG), and numerous individual volunteers and cooperators at National Park System units, colleges, and universities.

From the perspective of the Servicewide I&M Program, the primary focus (Level 1) of the geological inventory is

1. Assemble a bibliography of associated geological resources for National Park System units with significant natural resources,
2. Compile and evaluate a list of existing geologic maps for each unit,
3. Develop digital geologic map products, and
4. Complete a geological report that synthesizes much of the existing geologic knowledge about each park. The emphasis of the inventory is not to routinely initiate new geologic mapping projects, but to aggregate existing information and identify where serious geologic data needs and issues exist in the National Park System.

The NPS Geologic Resources Division is an active participant in the I&M Program and has provided guidance and funding in the development of inventory goals and activities. Geologic Resources Division administers the Abandoned Mine Lands (AML) and Geoscientists- in- the- Parks (GIP) programs which contribute to the inventory. National Park Service paleontologists, geologists, and other natural resource professionals also contribute to inventory planning and data. A major goal of the collaborative effort is to provide a broad baseline of geologic data and scientific support to assist park managers with earth resource issues that may arise.

For each National Park System unit, a cooperative group of geologists and NPS personnel (the “park team”) will be assembled to advise and assist with the inventory. Park Teams will meet at the each National Park System unit to discuss and scope the geologic resources and inventory, which is the subject of this report. If needed, a second meeting will be held at a central office to evaluate available geologic maps for digital production. After the two meetings, digital geologic map products and a geologic report will be produced. The report will summarize the geologic inventory activities and basic geology topics for each park unit. Due to the variety of geologic settings throughout the National Park System, each report will vary in subject matter covered, and section topics will be adapted as needed to describe the geologic resources of each unit. Whenever possible the scientific sections of the report will be written by knowledgeable cooperators and peer reviewed for accuracy and validity.

Gregson also presented a demonstration of some of the main features of the digital geologic map for the Black Canyon of the Gunnison National Monument and Curecanti National Recreation Area in Colorado. This has become the prototype for the NPS digital geologic map model as it ideally reproduces all aspects of a paper map (i.e., it incorporates the map notes, cross sections, and legend) with the added benefit of being a GIS component. It is displayed in ESRI ArcView shape files and features a built- in help file system to identify the map units. It can also display scanned JPG or GIF images of the geologic cross sections supplied with the map. The cross section lines (e.g., A–A') are subsequently digitized as a shape file and are hyperlinked to the scanned images.

The geologists at the workshop familiar with GIS methods were quite impressed with this method of displaying geologic maps digitally; Gregson is to be commended for his accomplishments.

Bruce Heise (NPS- GRD) followed with an introduction about the NPS Geologic Resources Division.

Interpretation

The GRI also aims to help promote geologic resource interpretation within the parks and GRD has staff and technology to assist in preparation of useful materials including developing site bulletins and resource management proposal (RMP) statements appropriate to promoting geology. Jim Wood (GRD) and Melanie Moreno (USGS–Menlo Park, CA) have worked with several other National Park System units in developing Web- based geology interpretation themes, and should be considered as a source of assistance should park staffs desire it.

Along the lines of interpretation of geology for the SEUG, it was suggested that they consider hiring a full-time geologist to be on staff to evaluate research proposals and generally assist all interpretive areas within the SEUG to find out what issues should be addressed. A geologist could add greatly to NABR, CANY, and ARCH because the primary theme of these parks is geologic; there would be no bridges, arches, or canyon (lands) without the underlying influence of geology and geologic processes upon this part of the world. A geologist would also certainly be active in establishing the most effective wayside exhibits aimed at informing the public about the geologic wonders of the area. A geologist can certainly assist in the presentation and interpretation of paleontologic resources and issues also.

Such a position could act as a liaison among various tour groups, researchers, field camps, and professional organizations that visit the area because of the spectacular geology. Geologic hazards would also be able to be more fully understood. Obviously, effective communication skills are a highly desirable quality for any applicant.

In the absence of such a position, the GRD is most willing to assist the SEUG in any geologic matters and issues should they desire. Please contact Bruce Heise or Tim Connors to discuss further matters regarding geologic resources.

UGA Guidebook on Utah's National and State Park Areas

Doug Sprinkel of the UGA announced that a guidebook treating the geology of 27 of Utah's national and state parks and monuments will be compiled for publication in September 2000. This compilation will be a snapshot into the geology of each park and covers most facets of what the GRI is trying to develop for each park for a final report (i.e., cross sections, simplified geologic map, general discussions of rocks, structure, unique aspects of park geology, and classic viewing localities). Each author will be *encouraged* to get with NPS staff interpreters to develop a product that aims at a wide audience (general public, technical audiences, and the teaching community). Authors for SEUG parks are as follows:

- Arches NP: Hellmut Doelling (UGS)
- Canyonlands NP: Donald Baars
- Natural Bridges NM: Jackie Huntoon, Russell Dubiel, Jack Stanesco

Also, a CD- ROM will be distributed with the publication featuring road and trail logs for specific parks as well as a photo glossary and gallery. Park authors are strongly encouraged to get with NPS staff to make sure that any trail logs do follow maintained trails and do not take visitors into unauthorized areas, or places where resources are fragile and would be disturbed by increased visitation (i.e., areas with crytptogamic soils).

The photo glossary will describe certain geologic features (i.e., what is crossbedding?). These will also be available as Web- downloadable Adobe Acrobat PDF files. The UGA cannot copyright this material because it is funded with state money, so it can be distributed widely and freely, which will also benefit the purposes of the GRI program. Additional reprints are not a problem because of the digital nature of the publication and the UGA board is committed to additional printings as needed. UGA normally prints 1,000 copies of their publications because they become dated after about five years; that will probably not be an issue for this publication. Prices for the full- color guidebook are estimated to be approximately $25/copy, and sales are expected to be high (exact estimates for Capitol Reef NM were 125 copies/year). A website for the guidebook is forthcoming in October 1999.

Field trips will be held in September 2000. Currently, four field trips are scheduled:

1. Arches National Park, Canyonlands National Park, Dead Horse Point State Park
2. Antelope Island State Park and Wasatch Mountain State Park

3. Southeast Utah Group National Park, Cedar Breaks National Monument, Snow Canyon State Park, and Quail Creek State Park
4. Dinosaur National Monument, Flaming Gorge National Recreation Area, and Red Fleet State Park

Note: Trips 1 and 2 will run concurrently and Trips 3 and 4 will also run concurrently.

Many other benefits are anticipated from this publication and are enumerated below:
- This type of project could serve as a model for other states to follow to bolster tourism and book sales promoting their state and its geologic features.
- Sandy Eldredge (UGS) will be targeting teaching communities for involvement in the field trips; hopefully teachers will pass on what they have learned to their young audience.
- The language is intended to appeal to someone with a moderate background in geology and yet will be very informative to the educated geologist.
- The publication may be able to serve as a textbook to colleges teaching courses about the geology of national parks (in Utah).
- A welcomed by- product could be roadlogs between parks in Utah for those visiting multiple parks, perhaps with a regional synthesis summarizing how the overall picture of Utah geology has developed.

Disturbed Lands

John Burghardt (GRD) has done work in Lathrop Canyon on reclaiming abandoned mineral lands (AML). His reports should be studied as a significant source of data for this area to determine if additional work needs to be performed. Dave Steensen (GRD) heads the AML Program and can also be contacted.

Paleontological Resources

The field trip at Arches National Park provided glimpses into the paleontological resources (dinosaur bones) near Delicate Arch. It has been suggested to keep this location low profile to minimize disturbances and potential theft or vandalism.

During the scoping session, the importance of a paleontological resource inventory for the Cedar Mountain and Morrison Formations near the Dalton Wells Quarry was discussed as being a priority. The important resources are likely to be dinosaur bones. A staff geologist or paleontologist would surely be useful for this purpose

Vince Santucci (NPS- GRD Paleontologist) will be co-authoring a paleontological survey of Arches National Park and detailing findings of resources within the park. Plants, invertebrates, and vertebrate tracksites are among the recognized paleontological resources within the Southeast Utah Group area parks.

Similar surveys have been done for Yellowstone and Death Valley National Parks and have shed valuable new information on previously unrecognized resources. These surveys involve a literature review; creation of a bibliography; recognition of type specimens, species lists, and maps (which are unpublished to protect locality information); and specific recommendations for protecting and preserving the resources.

Paleontological survey reports for Death Valley and Yellowstone National Parks are available at http://www2.nature.nps.gov/geology/paleontology/surveys/surveys.htm.

Paleontological resource management plans should be produced for Southeast Utah Group involving some inventory and monitoring to identify human and natural threats to these resources. Perhaps someone on the park staff could be assigned to coordinate paleontological resource management and incorporate any findings or suggestions into the parks general management plan (GMP). It would be useful to train park staff (including interpreters and law enforcement) in resource protection, as the fossil trade "black market" has become quite lucrative for sellers and often results in illegal collecting from federal lands.

Collections taken from this area that now reside in outside repositories should be tracked down for inventory purposes. Fossils offer many interpretive themes and combine a geology- biology link and should be utilized as much as possible in interpretive programs.

Status of Geologic Mapping Efforts for the SEUG

Status of Existing Maps

It should be noted that the following paper geologic maps exist:
- Arches National Park (*Geologic Map of Arches National Park and vicinity, Grand County, Utah* by Hellmut H. Doelling, 1985, scale 1:50,000*)*. The area was mapped at 1:24,000 scale, but compiled at 1:50,000 scale.
- Canyonlands National Park (*Geologic Map of Canyonlands National Park and Vicinity, Utah* by George Billingsley, Peter Huntoon, and William J. Breed, 1982, scale 1:62,500).
- Canyonlands National Park *(Bedrock Geologic Map of Upheaval Dome, Canyonlands NP, Utah* by Gene Shoemaker, Herkenhoff and Kriens, 1997, scale unknown).

George Billingsley noted that when he worked on the Canyonlands map, he mostly compiled previous material. He thought several additions to the Quaternary deposits and the placement of joints and fractures on the maps would improve the quality of the 1982 Canyonlands map. There are also some issues regarding assignment of the Page Sandstone, and the controversy of the Dewey Bridge Member of the Entrada versus the Carmel Formation being within the map area. He thinks eventually, the entire area should be compiled at *1:24,000* to better enhance features and add to resource management.

Jackie Huntoon has told Bruce Heise that she is working on a digital coverage for Natural Bridges, but needs the hypsography (contour lines) to complete her work.

Desired quadrangles that NRID has this coverage for are the following:

- The Cheesebox
- Woodenshoe Buttes
- Kane Gulch
- It is not sure if the coverage exists for the Moss Back Butte quadrangle; Joe Gregson will look into it.

Digitized Maps

The 1985 Arches map has been digitized into ArcInfo coverage by SEUG staff. The attribute quality is unknown however, and will be researched. NPS- GRI folks will work with SEUG GIS Specialist Gery Wakefield to learn more about this coverage

The 1982 Canyonlands map is not known to have been digitized at this point and hopefully can be done by the SEUG GIS staff. George Billingsley says that the Canyonlands Natural History Association has the original line work and mylars; Diane Allen said she will contact them to see if they still have this work.

The 1997 Upheaval Dome map is digitized as ArcInfo coverage and a copy was given to Craig Hauke (CANY) from George Billingsley. It also contains cross sections and a report.

UGS Mapping Activities in SEUG Area

Currently, the UGS is mapping in Utah at three different scales:

- 1:24,000 for high priority areas (i.e., national and state parks)
- 1:100,000 for the rest of the state
- 1:500,000 for a compiled state geologic map

The UGS plans to complete mapping for the entire state of Utah within 10–15 years at 1:100,000 scale. For 1:100,000 scale maps, their goal is to produce both paper and digital maps; for 1:24,000 scale maps, the only digital products will be from “special interest” areas (i.e., areas such as Southeast Utah Group and growing metropolitan Saint George). Grant Willis mentioned that the UGS simply does not have enough human or financial resources to do more areas at this scale. He also reiterated that UGS mapping goals are coincident with those of the National Geologic Mapping Program.

Grant Willis talked about the status of UGS mapping activities within the Southeast Utah Group area (see Attachment B).

30 × 60 sheets (at 1:100,000) for the area include the La Sal (greater Canyonlands area) and Moab (Arches National Park) sheets, which are currently in progress (paper and digital format).

Here is a brief summary of various mapping projects for SEUG parks from the UGS:

Park	Quadrangle	Status
ARCH	Klondike Bluffs	UGS (Doelling) mapping in progress
	Mollie Hogans	UGS (Doelling) mapping in progress
	Cisco SW	Slated for future work
	Big Bend	Paper map published 1998; not digitized
	The Windows Section	UGS (Doelling) mapping in progress
	Merrimac Butte	In publication
	Gold Bar Canyon	Published
	Moab- 16	Ready for press
	Moab (30 × 60)	Digital and printed map in progress
CANY	Hanksville	Nothing currently; hopefully in a few years
	La Sal	Digital and printed map in progress
NABR	Hite Crossing	Nothing slated at this time
	Blanding	

Other Sources of Natural Resources Data for SEUG

- The UGS has a significant quadrangle database that they have furnished to NRID for the entire state of Utah.
- NRID has compiled a geologic bibliography for numerous parks and monuments, including all parks in the Southeast Utah Group.
- SEUG GIS specialist showed a digitized version of Hellmut Doelling’s 1985 map as and ArcInfo coverage; attribution needs to be checked; other coverages should be sought that may exist from the previous GIS specialist.
- GRD has several entries regarding abandoned mineral land (AML) sites in their database that should be checked for data validity and compared with park records; John Burghardt (GRD) should be contacted regarding this.
- The Arches National Park visitor center sells a publication that has an inventory of all the arches at the park.
- The UGS has compiled a CD- ROM with well locations, pipelines, etc. for the state of Utah; GRD should obtain a copy of this. Park staffs may also desire copies.

Geologic Hazards

Numerous issues relate to geologic hazards in and around the Southeast Utah Group parks. A brief list of some hazards mentioned during the scoping session follow:

- Landslide and rockfall potential along all roads that occasionally cause road closures; of special note was the problem with the main road in Arches, just above the visitor center.
- Landscape Arch (ARCH) collapsed in a few places several years ago and was recorded by a tourist.
- Swelling soils associated with bentonitic shales of the Chinle, Morrison, and Mancos Formations
- Radon potential associated with mine closures
- Earthquake potential along the Moab Fault

Potential Research Topics for Southeast Utah Group

A list of potential research topics includes studies of the following:

- What are the connections between gypsiferous rocks and cryptobiotic soils/crusts? Why are the crusts healthier on the gypsum- bearing rocks?
- How long will Delicate Arch stand?
- Engineering studies to determine hazards to visitors; use strain meter
- Use High resolution GPS to detect moving, swelling, and collapse in areas of the parks
- Rock color studies
- Subsurface seismic work for voids in the Needles around synclines and salt dome structures
- Locate real unconformity between Entrada Moab Tongue and abutting formations

Action Items

Many follow- up items were discussed during the course of the scoping session and are reiterated by category for quick reference.

Interpretation

More graphics and brochures emphasizing geology and targeting the average enthusiast should be developed. If Southeast Utah Group needs assistance with these, please consult Jim Wood (GRD) (jim_f._wood@nps.gov) or Melanie Moreno (USGS–Menlo Park) (mmoreno@usgs.gov).

- Consider the possibility of hiring a full- time geologist to handle geologic issues for the SEUG; in the absence of this consult with GRD for assistance in geologic matters.

UGA Guidebook

- Attempt to plant the seeds of this concept to other states for similar publications involving local area geology. Such publications are especially useful for the geologic resources inventory.
- Have authors prepare logs that are "sensitive" to delicate areas in the park (i.e., where less user impact is desired).

Paleontological Resources

- For now, try to minimize location disclosure of vertebrate sites to minimize disturbances and the potential for theft or vandalism.
- Develop an in- house plan to inventory, monitor, and protect significant paleontological resources from threats; assign staff to oversee especially in regard to the Dalton Wells area.
- Locate fossils collected from the park residing in outside repositories.

Geologic Mapping

- Attempt to complete digital coverage for the entire SEUG area from existing maps
- Locate already existing digital coverages (e.g., Doelling's 1985 Arches map).
- Work closely with UGS to finish paper and digital coverage of SEUG area where maps are lacking.
- Work with cooperators (e.g., NABR–Jackie Huntoon) to ensure there work could be incorporated into the master plan of the geologic resources inventory program.

Natural Resource Data Sources

- Examine GRD databases for AML sites and disturbed lands for data validity.
- Attempt to locate other digital coverages from the previous SEUG GIS specialist (Eric) for Gery Wakefield's (current SEUG GIS specialist) inventory.

Miscellaneous

- Review proposed research topics for future studies within Southeast Utah Group parks.
- Promote sensitivity of delicate resources (e.g., crusts) to researchers, and visiting park groups.

Attachment A: Southeast Utah Group Geological Resources Inventory Workshop Participants

Name	Affiliation	Phone	E-Mail
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Christine Turner	USGS	(303) 236- 1561	Cturner@usgs.gov
Fred Peterson	USGS	(303) 236- 1546	Fpeterson@usgs.gov
Jack Stanesco	Red Rocks CC	(303) 914- 6290	Jack.Stanesco@rrcc.cccoes.edu
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Helmut Doelling	UGS	(435) 835- 3652	None
Doug Sprinkel	UGS / UGA	(801) 782- 3398	Sprinkel@vii.com
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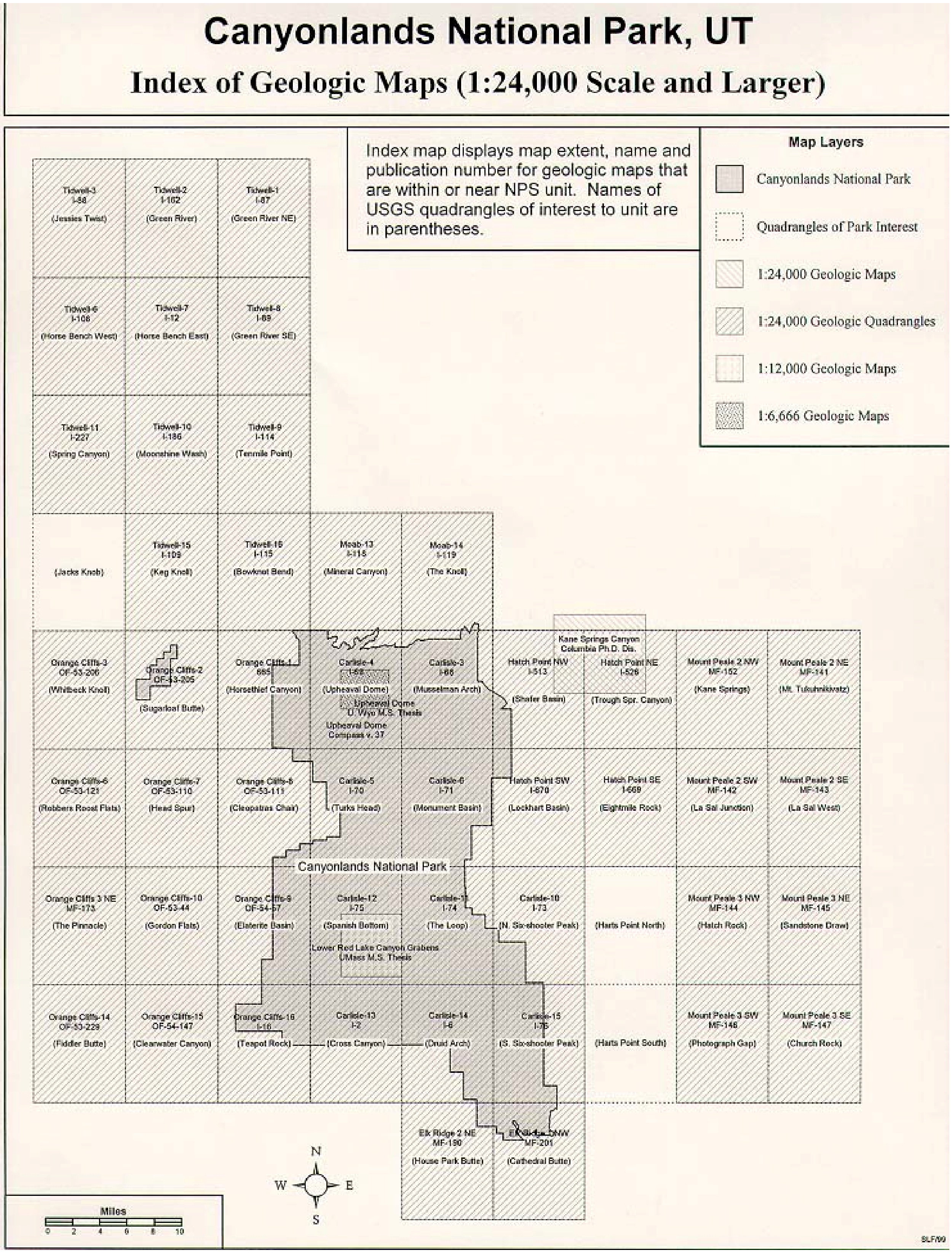
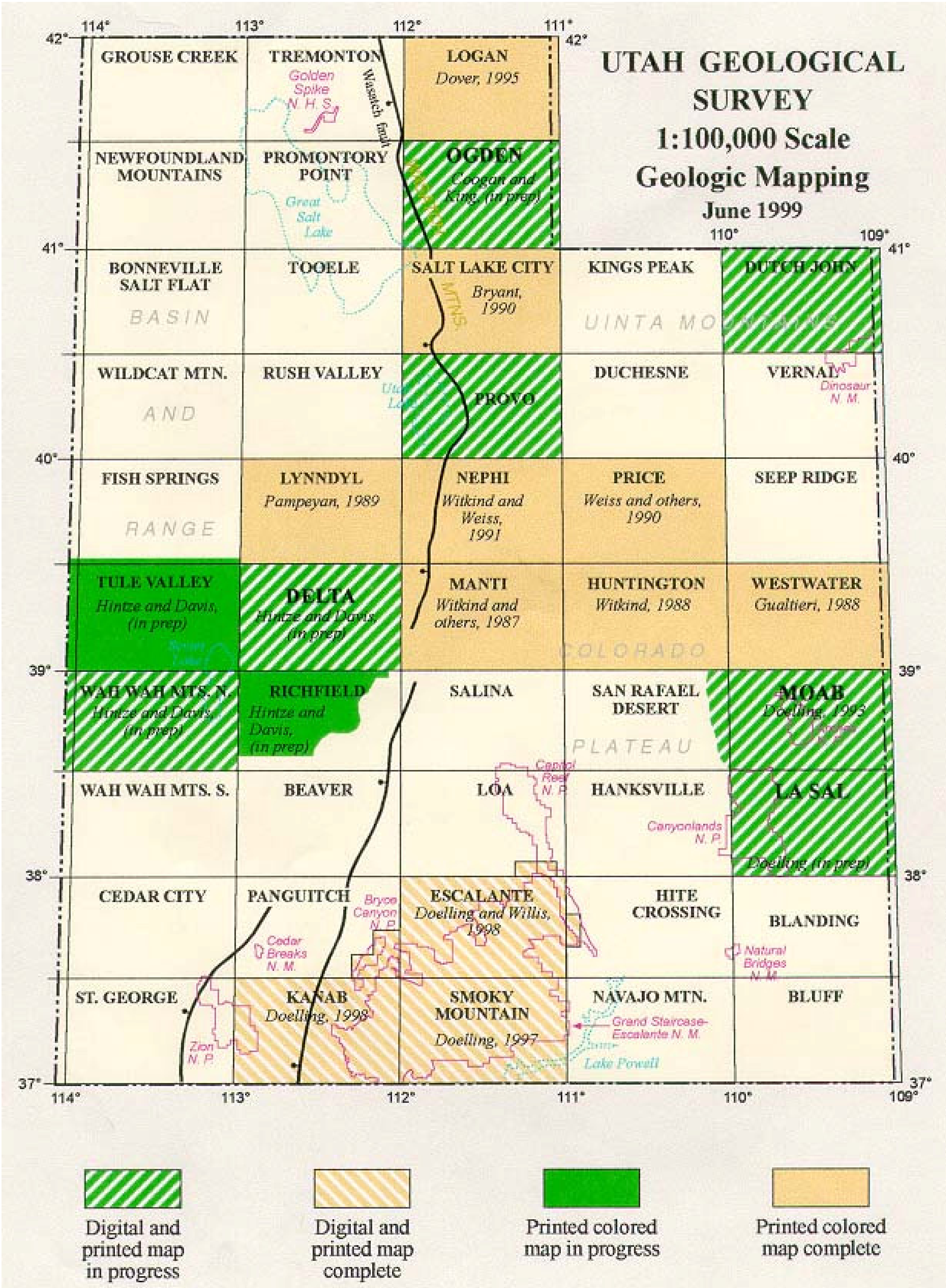
Diane Allen	NPS, ARCH	(435) 259- 8161	Diane_Allen@nps.gov
Paul Henderson	NPS, SEUG	(435) 259- 3911 ext. 2140	Paul_Henderson@nps.gov

Attachment B: Quadrangle Maps for Southeastern Utah Group Parks




UTAH GEOLOGICAL SURVEY
1:100,000 Scale Geologic Mapping
June 1999
GROUSE CREEK
TREMONTON
Golden Spike N. H. S.
Wasatch fault
LOGAN
Dover, 1995
NEWFOUNDLAND MOUNTAINS
PROMONTORY POINT
Great Salt Lake
OGDEN
Coogan and King, (in prep)
BONNEVILLE SALT FLAT
BASIN
TOOELE
SALT LAKE CITY
Bryant, 1990
MTNS.
KINGS PEAK
UINTA MOUNTAINS
DUTCH JOHN
WILDCAT MTN.
AND
RUSH VALLEY
Utah Lake
PROVO
DUCHESNE
VERNAL
Dinosaur N. M.
FISH SPRINGS
RANGE
LYNNDYL
Pampeyan, 1989
NEPHI
Witkind and Weiss, 1991
PRICE
Weiss and others, 1990
SEEP RIDGE
TULE VALLEY
Hintze and Davis, (in prep)
DELTA
Hintze and Davis, (in prep)
MANTI
Witkind and others, 1987
HUNTINGTON
Witkind, 1988
WESTWATER
Gualtieri, 1988
COLORADO
WAH WAH MTS. N.
Hintze and Davis, (in prep)
RICHFIELD
Hintze and Davis, (in prep)
SALINA
SAN RAFAEL DESERT
PLATEAU
MOAB
Doelling, 1993
WAH WAH MTS. S.
BEAVER
LOA
Capitol Reef N. P.
HANKSVILLE
Canyonlands N. P.
LA SAL
Doelling (in prep)
CEDAR CITY
PANGUITCH
Bryce Canyon N. P.
Cedar Breaks N. M.
ESCALANTE
Doelling and Willis, 1998
HITE CROSSING
BLANDING
Natural Bridges N. M.
ST. GEORGE
Zion N. P.
KANAB
Doelling, 1998
SMOKY MOUNTAIN
Doelling, 1997
NAVAJO MTN.
Grand Staircase-Escalante N. M.
Lake Powell
BLUFF
114°
113°
112°
111°
110°
109°
42°
41°
40°
39°
38°
37°
Digital and printed map in progress
Digital and printed map complete
Printed colored map in progress
Printed colored map complete

Appendix C: Geoindicators Scoping Summary

The following excerpt is from the geoindicators scoping summary for four National Park Service units in southeastern Utah, including Canyonlands National Park. The scoping meeting occurred on June 3- 6, 2002, therefore, the contact information and Web addresses referred to herein may be outdated. Please contact to the Geologic Resources Division for current information. Also, please refer to the included CD for the complete geoindicators report.

Staff of the National Park Service, Utah Geological Survey, U.S. Geological Survey, Bureau of Land Management, Northern Arizona University, and Brigham Young University participated in a geoindicators scoping meeting in Moab, Utah, for four National Park Service units in southeastern Utah. The four parks were Arches National Park (ARCH), Canyonlands National Park (CANY), Capitol Reef National Park (CARE), and Natural Bridges National Monument (NABR).

Purpose of Meeting

The purpose of the meeting was to bring together park staff, geoscientists, and other resource specialists to address the issue of human influences on geologic processes in the four park areas. The group used collective knowledge of the four parks' geology and natural resources to identify the geologic processes active in the parks, to identify the human activities affecting those processes, and to develop recommendations for long- term monitoring of geoindicators in conjunction with park Vital Signs monitoring.

In addition, the Northern Colorado Vital Signs Network is coming on- line in fiscal year 2002 and will be receiving its first funding for Vital Signs monitoring. The scoping meeting was timed so the Network could use the information gained during the meeting in the Vital Signs selection process.

This report summarizes the group's discussions and provides recommendations for studies to support resource management decisions, inventory and monitoring projects, and research needed to fill data gaps.

Government Performance and Results Act Goal Ib4

This meeting satisfies the requirements of the GPRA Goal Ib4, which is a knowledge- based goal that states, "Geological processes in 53 parks (20% of 265 parks) are inventoried and human influences that affect those processes are identified." The goal was designed to improve park managers' capabilities to make informed, science- based decisions with regards to geologic resources. It is the intention of the goal to be the first step in a process that will eventually lead to the mitigation or elimination of human activities that severely impact geologic processes, harm geologic features, or cause critical imbalance in the ecosystem.

Because GPRA Goal Ib4 inventories only a sampling of parks, information gathered at the four parks may be used to represent other parks with similar resources or human influences on those resources, especially when findings are evaluated for Servicewide implications.

Geoindicator Background Information

An international Working Group of the International Union of Geological Sciences developed geoindicators as an approach for identifying rapid changes in the natural environment. The National Park Service uses geoindicators during scoping meetings as a tool to fulfill GPRA Goal Ib4. Geoindicators are measurable, quantifiable tools for assessing rapid changes in earth system processes. Geoindicators evaluate 27 earth system processes and phenomena (Appendix A) that may undergo significant change in magnitude, frequency, trend, or rates over periods of 100 years or less and may be affected by human actions (Appendix B). Geoindicators guide the discussion and field observations during scoping meetings (Appendix C). The geoindicators scoping process for the National Park Service was developed to help determine the studies necessary to answer management questions about what is happening to the environment, why it is happening, and whether it is significant.

Aspects of ecosystem health and stability are evaluated during the geoindicators scoping process. The geologic resources of a park—soils, caves, streams, springs, beaches, volcanoes, etc.—provide the physical foundation required to sustain the biological system. Geological processes create topographic highs and lows; affect water and soil chemistries; influence soil fertility and water- holding capacities, hillside stability, and the flow regimes of surface water and groundwater. These factors, in turn, determine where and when biological processes occur, such as the timing of species reproduction, the distribution and structure of ecosystems, and the resistance and resilience of ecosystems to human impacts (Appendix D).

Park Selection

These parks were selected for a number of reasons, including the fact that the parks represent the four of the five parks in the Northern Colorado Plateau Prototype Cluster. These prototype parks will be the foci of research and development for protocols associated with vital- signs monitoring at NCPN parks and monuments. Geologic resources and processes found in these four parks are generally representative of those found throughout the rest of the NCPN, and considerable geologic research has been conducted in them previously.

Summary of Results and Recommendations

During the scoping meeting, geoindicators appropriate to Arches National Park, Canyonlands National Park, Capitol Reef National Park, and Natural Bridges National Monument were addressed. Of the 27 geoindicators (Appendix A), 21 were recognized as on-going processes to varying degrees in the four parks. An additional four geologic issues that are not part of the original geoindicators were also discussed (i.e., fire occurrence, atmospheric deposition, paleontological resources, and climate), as was an issued called "ecosystem response to geomorphic processes." The issues surrounding each geoindicator were identified, and participants rated the geoindicator with respect to the importance to the ecosystem, human impacts, and significance for resource managers (Geoindicators table). A compilation of the notes taken during the scoping session (Appendix G) and field trip (Appendix H) are included in the appendices. These notes may highlight additional information regarding geoindicators that may be useful to resource managers.

During the geoindicators scoping meeting, participants identified studies to support resource management decisions, inventory and monitoring projects, and research to fill data gaps at all four parks. The recommendations that follow are not listed in any order of priority, but are intended to help guide park managers when making decisions regarding natural resource management needs. The recommendations that are listed are by no means inclusive of all possible geological research and monitoring.

Significant Geoindicators

The following is a summary of the results for the 11 geoindicators that rated the highest in all three categories, as well as the recommendations for these geoindicators that were developed during the meeting. A summary of the scoping session discussion and the field trip are included in Appendix G and H, respectively. These notes highlight additional information regarding geoindicators that may be useful to resource managers.

Desert Surface Crusts (Biological and Physiochemical) and Pavements

Biological soil crusts composed primarily of varying proportions of cyanobacteria, lichens, and mosses are important and widespread components of terrestrial ecosystems in all four parks, and greatly benefit soil quality and ecosystem function. They increase water infiltration in some soil types, stabilize soils, fix atmospheric nitrogen for vascular plants, provide carbon to the interspaces between vegetation, secrete metals that stimulate plant growth, capture nutrient- carrying dust, and increase soil temperatures by decreasing surface albedo. They affect vegetation structure directly due to effects on soil stability, seedbed characteristics, and safe-site availability, and indirectly through effects on soil temperature and on water and nutrient availability. Decreases in the abundance of biological soil crusts relative to physicochemical crusts (which can protect soils from wind erosion but not water erosion, and do not perform other ecological functions of biological crusts) can indicate increased susceptibility of soils to erosion and decreased functioning of other ecosystem processes associated with biological crusts.

Human Impacts
Off- trail use by visitors, past trampling by cattle in Arches and Canyonlands national parks, and present trampling by cattle in Capitol Reef National Park have damaged soil crusts significantly in some areas . Soil nutrient cycles, as well as most other benefits of biological soil crusts, have been compromised in these areas.

Recommendations
1. Inventory condition and distribution of biological soil crusts.
2. Investigate connection between ecosystem function and biological crusts.
3. Map crust communities in relation to environmental factors.
4. Study crust recovery rates and susceptibility to change.
5. Study crust population dynamics and conditions.

Wind Erosion and Deposition

In addition to water, wind is a major force that can redistribute soil and soil resources (e.g., litter, organic matter, and nutrients) within and among ecosystems. Erosion and deposition by wind is important in all four parks and can be accelerated by human activities. Accelerated losses of soil and soil resources by erosion can indicate degradation of arid- land ecosystems because ecosystem health is dependent on the retention of these resources.

Human Impacts
Trampling and vegetation alteration by livestock as well as human recreational activities such as hiking, biking, and driving off of established trails and roads can destabilize soils and increase soil susceptibility to wind erosion. Some localized heavy visitation areas within parks have seen crust death by burial from windblown sands when nearby crusts have been trampled, such as in the Windows area of Arches National Park

In addition, wind erosion and sediment transport may be strongly impacted by land- use practices outside the parks. Eolian sand from disturbed surfaces may saltate onto undisturbed ground, burying and killing vegetation and/or biological soil crusts, or breaking biological soil crusts to expose more soil to erosion. Because park management practices limit or prohibit off- road travel, human impacts within the parks primarily are associated with off- trail hiking in high- use areas. Where livestock grazing or trailing is still permitted (e.g., CARE), accelerated soil erosion can be more extensive.

Recommendations

1. Monitor movement of soil materials (see Recommendations table).
2. Investigate ecosystem consequences of movement (Contact: Jason Neff, 303- 236- 1306, jneff@usgs.gov)
3. Investigate natural range of variability of soil movement in relation to landscape configuration and characteristics. (Contact: Jason Neff, 303- 236- 1306, jneff@usgs.gov)

Stream Channel Morphology

The morphology of stream channels impacts the vegetative structure of the riparian corridor, affects the height of the water table, and affects the energy of water flow downstream (which affects erosion rate and water quality). Stream channels are vital components of aquatic and riparian ecosystems in these arid- land parks.

Human Impacts

Potential for human impact on stream channel morphology is great. These impacts include building parking lots and structures in or near channels, building structures in floodplains (e.g., culverts and bridges), livestock grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion.

Recommendations

1. Conduct hydrologic condition assessment to identify actual and potential "problem reaches" for prioritized monitoring.
2. Monitor "problem reaches" [?] with repeat aerial photographs.
3. Monitor "problem reaches" [?] with repeated cross-sections. Some data are available for Capitol Reef, Canyonlands, and Arches national parks (see Recommendations table).

Stream Sediment Erosion, Storage and Load

Participants added "erosion" to this geoindicator in order to clarify and encompass the total geomorphic picture regarding stream function. Stream sediment erosion, storage, and load is important to the ecosystem because sediment loads and distribution affect aquatic and riparian ecosystems, and because sediment loading can result in changes to channel morphology and overbank flooding frequency.

Human Impacts

The potential for human impact to stream sediment erosion, storage, and load is great. These impacts include building parking lots and structures in or near channels, building structures in floodplains structures (e.g., culverts and bridges), grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion.

Recommendations

1. Conduct research concerning ungaged stream sediment storage and load. There are no data available except on the main stem of the Colorado River at Cisco, Utah, and the Green River at Green River, Utah).
2. Measure sediment load on streams of high- interest streams for comparative assessment. Data will provide information for making management decision.

Streamflow

Streamflow is critical to the maintenance of aquatic and riparian ecosystems. Streamflow impacts the structure of the riparian corridor, affects the height of the water table, and affects water quality and erosion rates.

Human Impacts

The potential for human impact on streamflow is great. These impacts include building parking lots and structures in or near channels, building structures in floodplains (e.g., culverts and bridges), grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion.

Recommendations

1. Identify important hydrologic systems that would benefit from knowledge of streamflow. Existing gauging stations are located on the Green River (Green River, Utah), San Rafael River (near Green River, Utah.), Fremont River (at Cainville, Utah, and above Park at Pine Creek.), and on the Muddy River. Many other gauging stations exist (see USGS Web site). Additional data exists for streams in Capitol Reef National Park and for Courthouse Wash in Arches National Park. Other relevant data exists with the local U.S. Geological Survey, Water Resources Division.
2. Research effects of land- use and climatic variation on streamflow.
3. Investigate paleoflood hydrology.

Surface Water Quality

A detailed understanding of the issues and what has been done with regards to water quality data for the four NPS units, see Don Weeks June, 2002, trip report in Appendix J. There are a number of park- specific water resource reports cited in the report that are particularly pertinent.

Human Impacts

The potential for negative affects on groundwater quality by human activity is significant. The following are specific issues that could impact groundwater quality:

- Herbicide use to decrease tamarisk populations.
- Trespass cattle at springs.
- Abandoned oil and gas wells within and close to NPS boundaries may result in saline waters infiltrating into groundwater supplies. Abandoned uranium mines and mills.
- Impacts from recreational uses (these have not been quantified).

Human Impacts

- Old landfill in Needles District (approx. 1 mile from Visitor Center, and 3000 ft from a domestic well) of CANY had unregulated dumping from 1966- 1987.
- Texas Gulf Potash Mine located downriver from Moab on the Colorado River.

Recommendation

1. Obtain information about existing baseline water quality data for all four parks (Contact: Don Weeks, 303- 987- 6640, don_weeks@nps.gov).

Wetlands Extent, Structure, and Hydrology

Wetlands are important ecosystems because they stabilize stream banks, act as filters to improve water quality, attenuate flood waters, enhance biodiversity (important habitat for amphibians, reptiles, birds, and Threatened and Endangered Species), are highly productive in terms of biomass and nutrient productivity, and are valuable water sources for wildlife and recreationists.

Human Impacts

The potential for human impact on wetlands is great. These impacts include building parking lots and structures in or near channels, building structures in floodplains (e.g., culverts and bridges), grazing in uplands and stream channels, roads and trails up streambeds, introduction of exotic species, and impacts from flow regulation and diversion. In addition, agricultural activities and past extirpation of beaver have affected wetlands.

Recommendations

1. Inventory location, character, and conditions of wetlands in all four parks.
2. Inventory distribution of exotic species in wetlands.
3. Monitor groundwater levels and surface elevations.
4. Investigate age- structure of woody riparian plants in relation to land use.
5. Investigate linkages between amphibian parameters and wetland health.

Groundwater Quality

The quality of the groundwater in the parks has a high impact on hanging gardens, which are located in all four parks. Hanging gardens are unique features that contain rare and unique plant species, and provide important wildlife habitat. Groundwater quality is also a safety and health issue regarding water quality for human use.

Human Impacts

The potential for negative affects on groundwater by human activity is significant. All four parks identified specific issues that could impact groundwater quality.

Human Impacts

- Old landfill in the Needles District had unregulated dumping from 1966- 1987.
- Oil well sites had improper dewatering.
- The effects of mining and oil and gas drilling are unknown.

Recommendations

1. Locate and inventory all seeps, springs, and hanging gardens.
2. Prioritize seeps, springs, and hanging gardens for assessment of water quality.
3. Acquire plugging records of oil and gas wells potentially connected to park groundwater systems (Contact: Bob Higgins, 303- 969- 2018, bob_higgins@nps.gov).
4. Use geochemical indicators to investigate groundwater flow areas, flow directions and recharge area, and groundwater age.
5. Identify and study potential sources for groundwater quality impacts at all four parks, including those listed above (Contact: Don Weeks, 303- 987- 6640, don_weeks@nps.gov).

Groundwater Level and Discharge

Outside the river corridors in Canyonlands and Capitol Reef national parks, groundwater supplies much of the water available for wildlife, and supplies 100% of the park's water supply for human use.

Human Impacts

Groundwater is a limited resource, and the potential for human impact is great. Current human impacts are poorly understood.

Recommendations

1. Inventory and research are needed concerning groundwater quality, level, and discharge.
2. Install transducers and dataloggers in wells.
3. Develop methods for measuring water discharge from seeps and hanging gardens (Contact: Bob Webb, 520- 670- 6671, rhwebb@usgs.gov).
4. Investigate additional methods to characterize groundwater recharge areas and flow directions (Contacts: Charlie Schelz, 435- 719- 2135, charlie_schelz@nps.gov and Rod Parnell, 928- 523- 3329, roderic.parnell@nau.edu).

Soil Quality

Soil quality affects moisture retention, nutrient cycling, soil- food webs, and aggregate structure. Soil also provides biogeochemical and hydrologic support for terrestrial productivity, especially vegetation growth. Soil quality degradation results in loss of certain ecosystem functions.

Human Impacts

Due to past and present grazing in the parks, nutrient cycles have not recovered.

Recommendations

1. Assess existing soil- crust conditions in relation to potential (as an indicator of soil quality) and in relation to soil maps.
2. Repeatedly measure soil quality in disturbed sites to gain understanding of recovery rates in relation to environmental factors.
3. Quantify natural range of variability in quality in relation to environmental factors.

4. Develop predictive model for potential biological soil crust distribution/structure/function in relation to environmental factors.
5. Investigate susceptibility to change (e.g., climate and UV).
6. Study resistance and resilience of soil to disturbances.

Soil and Sediment Erosion and Deposition by Water

During the discussion of this geoindicator, participants chose to focus on water transport and deposition, therefore the words, "and deposition by water" were added to this geoindicator. Transport and/or loss of soil may result in degradation of soil quality (see Soil quality geoindicator).

Human Impacts
In general, past grazing practices has caused soil erosion in all four parks. There is still occasional trespass of cattle in Arches and Canyonlands national parks and Natural Brides National Monument.

Recommendations
1. Investigate/develop methods for monitoring erosion and deposition quantitatively and affordably, and determine the best locations to monitor (Contact: Bob Webb, 520- 670- 6671, rhwebb@usgs.gov).
2. Assess conditions of soil erosion. (e.g., qualitative hydrologic function).

Ecosystem Response to Geomorphic Processes

Because many types of ecosystems are highly dependent on the geomorphic process and substrate, ecosystem response to geomorphic processes is highly important to park ecosystems. Disturbance to ecosystems is inevitable, whether the disturbance is human or natural caused. Management actions that attempt to mitigate disturbances, and particularly restoration of disturbed areas, may be influenced by the types of geomorphic processes involved and/or the nature of geomorphic substrates. Knowledge of predicted ecosystem responses to disturbances may affect the decision of whether to actively rehabilitate a disturbed site or whether to allow it to recover naturally. If active rehabilitation or restoration is chosen, this knowledge should determine what types of species are suitable for the underlying geomorphic conditions. Land- use practices, as well as climatic fluctuations may have an impact on ecosystem response. The perceived significance by managers depends upon need in the wake of an important disturbance that may instigate a management response.
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Recommendations
1. Acquire high quality surficial geology, soil, and vegetation maps for all four parks. Current availability of soil and geologic mapping varies among the parks.
2. Determine what to monitor, where, and with what attributes/indicators.
3. Research spatial and temporal relations among ecosystem structure and function, geologic substrates, and geomorphic processes.
4. Assess change- detection methods.

Geoindicator table for Arches, Canyonlands, Capitol Reef National Parks and Natural Bridges National Monument

Geoindicators	Importance to park ecosystem				*Human Impact				**Significance to natural resource managers			
	CANY	ARCH	NABR	CARE	CANY	ARCH	NABR	CARE	CANY	ARCH	NABR	CARE
ARID AND SEMIARID												
Soil crusts and pavements	5	5	5	5	5	5	5	5	5	5	5	5
Dune formation and reactivation	3	3	1	3	1	2	1	3	1	2	1	4
Dust storm magnitude, duration and frequency	1	1	1	1	5 1	5 2	5 1	5 3	3	3	3	3
Wind erosion (and deposition)	5	5	5	5	5 1	5 2	5 1	5 3				
SURFACE WATER												
Stream channel morphology	5	5	5	5	5	5	5	5	5	5	5	5
Stream sediment storage and load	5	5	5	5	5	5	5	5	5	5	5	5
Streamflow	5	5	5	5	5	5	5	5	5	5	5	5
Surface water quality	5	5	5	5	5	5	5	5	5	5	5	5
Wetlands extent, structure, hydrology	5	5	5	5	5	5	5	5	5	5	5	5
GROUNDWATER												
Groundwater quality	5	5	5	5	U	4	U	4	4	4	4	3
Groundwater level (and discharge)	5	5	5	5	5	5	5	5	5	5	5	5
SOILS												
Soil quality	5	5	5	5	1 5	1 5	1 5	1 5	5	5	5	5
Soil and sediment erosion (and deposition by water)	4	4	4	5	3 5	1 5	1 5	3 5	4	4	4	5
Sediment sequence and composition	1	1	1	1	4	4	4	5	3	3	3	3
HAZARDS												
Landslides, rockfalls, debris flows	3	2	2	3	1	1	1	1	1	1	1	2
Seismicity	2	1	1	1	3	3	0	0	1	1	1	1
Surface displacement (salt dissolution)	3	2	1	2	0	0	0	0	2	1	1	1
Fire occurrence	2	2	1	1	5	5	5	5	1	1	1	1
OTHER												
Atmospheric deposition (N, SO_4)	1	1	1	1	3	3	3	3	1	1	1	1
Paleontological resources	1	1	1	1	1	3	3	3	1	3	3	3
Climate	5	5	5	5	1	1	1	1	5	5	5	5
Ecosystem structure and function characteristics as integrated indicators of geophysical (i) environments, (ii) processes, and (iii) changes/disturbances.	5	5	5	5	5#	5#	5#	5#	5	5	5	5
0 - Not Applicable (N/A) 1 - LOW or no substantial influence on, or utility for 3 - MODERATELY influenced by, or has some utility for 5 - HIGHLY influenced by, or with important utility for U - Unknown; may require study to determine applicability	*Includes current and potential impacts. If 2 rows, top = impacts of out- of- park activities on within- park condition; bottom = impacts of within- park activities. **Synthesis of first two columns and other miscellaneous factors #process specificity											

Canyonlands National Park

Geologic Resource Evaluation Report
NPS D-167, September 2005

National Park Service

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Natural Resource Stewardship and Science

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The Natural Resource Program Center consists of six divisions: Air Resources, Biological Resource Management, Environmental Quality, Geologic Resources, Natural Resource Information, and Water Resources Divisions. The Geologic Resources Division, in partnership with parks and others, works to protect, preserve, and understand the geologic resources of the National Park System and to protect park resources from the adverse affects of mineral development in and adjacent to parks. One of the functions of the Division, carried out in the Planning Evaluation and Permits Branch is the Geologic Resource Evaluation Program. This program develops digitized geologic maps, reports, and bibliographies for parks.

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Production of this geologic report was facilitated by the NPS Colorado Plateau Cooperative Ecosystem Studies Unit.

National Park Service
U.S. Department of the Interior

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